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INTEGRATED CONTROL OF COMBINED SEWER REGULATORS USING WEATHER RADAR

by

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16. ABSTRACT

Integrated operation was simulated of ten dynamic combined sewer regulators on a Montreal interceptor. In general, when no in-line or other in-system storage can be called upon, no advantage over local automatic-dynamic regulator control can be obtained by integrated operation of regulators unless expected flowrates to the interceptors can be estimated in advance of their actual occurrence, and unless an operational bias is introduced which either minimizes overflows from only some of the regulators on an interceptor or favors the timing of overflows from all of the outlets, such as during the initial storm period. Detailed review of digital recording weather radar capabilities indicated that it is potentially the best rainfall estimation means for accomplishing the runoff prediction that would be required. Auxiliary uses for such radars in metropolitan areas were considered, particularly potentials for their exploitation as part of urban flood warning systems, using metropolitan Denver as a case study. Consideration was also given to potentials for exploiting in-line storage induced in collector sewers to gain greater flexibility with integrated regulator operation.

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FOREWORD

The Environmental Protection Agency was created because of the increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research, a most vital communications link between the researcher and the user community.

Explored in this study was the possibility of reducing the extent of overflows from combined sewer systems. The means for increasing the abatement efficiency of such systems was postulated as the real-time, integrated operation of all interceptor regulators in conjunction with digital recording weather radar.

Francis T. Mayo
Director
Municipal Environmental Research
Laboratory

ABSTRACT

Abatement of pollution from combined sewer overflows has been regarded by some localities as requiring the addition of extensive new storage, transport and treatment facilities to their systems. The central purpose of the study reported herein was to explore the technical feasibility of some less costly measures that might prove adequate for other communities with less stringent abatement requirements, namely the possibility of reducing the extent of overflows from conventional combined sewer systems that typically divert some stormwater via regulators to interceptor sewers. The means for increasing the abatement efficiency of such systems was postulated as the real-time, integrated operation of all interceptor regulators from a central computer. Dynamic regulators are normally actuated on the basis of local control whereby the interceptor flow stage in the immediate locality of a given regulator is maximized.

When no in-line or other in-system storage can be called upon, no advantage over local automatic dynamic regulator control can be obtained by integrated operation of regulators unless expected flowrates to the interceptors can be estimated in advance of their actual occurrence, and unless an operational bias is introduced which either minimizes overflows from only some of the regulators on an interceptor or favors the timing of overflows from all of the outlets, such as during the initial storm period. Computations for an actual system covering a summer season indicate that, even when a time-varying pollutant parameter is accounted for, the reduction in mass of a pollutant entering the receiving water under integrated operation of regulators may be only marginal. Consideration is given to the potentials for exploiting in-line storage induced in collector and outfall sewers to gain greater flexibility with integrated regulator operation.

As part of an introduction to digital recording weather radar for non-meteorologists, newly available rainfall tracking, measuring and predicting capabilities of such radars are described. Use of these capabilities would be required to achieve maximum effective integrated regulator control.

A thesis of the study was that the attractiveness of an integrated regulator control system would be limited if it was necessary to dedicate a radar mostly to that service. Accordingly, auxiliary uses for radars in metropolitan areas are given consideration, particularly for urban flood warning systems.

This report was submitted in fulfillment of research Grant No. R806702 under the primary sponsorship of the U.S. Environmental Protection Agency, awarded to the American Society of Civil Engineers on behalf of its Urban Water Resources Research Council. Work was completed as of June, 1980.

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SECTION 1

INTRODUCTION

OBJECTIVES

Abatement of pollution from combined sewer overflows has been regarded in some localities as requiring the addition of extensive new storage, transport and treatment facilities to their systems. The central purpose of the study reported herein was to explore the technical feasibility of some less costly measures that might prove adequate for other communities with less stringent abatement requirements. At the end of 1979, the U.S. General Accounting Office challenged the need for large construction projects because of their high costs,(1) which suggests that more consideration may be given in future to less costly solutions.

Explored in this study was the possibility of reducing the extent of overflows from conventional combined sewer systems that typically divert some stormwater via regulators to interceptor sewers. The means for increasing the abatement efficiency of such systems was postulated as the real-time, integrated operation of all interceptor dynamic regulators from a central computer. As will be shown, when no in-line or other in-system storage can be called upon, no advantage over independently operated regulators can be obtained without a companion capability for estimating expected flowrates to an interceptor in advance of their occurrence. Recent development of storm tracking and rainfall measurement and prediction capabilities using special weather radars made exploration of the integrated operation hypothesis particularly timely.

A thesis of this study was that the attractiveness of an integrated control system would be limited if it was necessary to dedicate a radar mostly to that service. Therefore, auxiliary uses for radars in metropolitan areas are given consideration, particularly for urban flood warning systems.

Latitude in the operation of a combined sewer system is determined by the degree of flexibility available in the system for manipulation. In general, only by adding new storage capacity can flexibility, and hence operational latitude, of a conventional system be increased. Altogether new off-line storage is very costly. There have been a few instances where in-line storage has been induced in existing collector and outfall sewers by installing adjustable dams or gates in them, at relatively very modest cost. Consideration is given herein to the potentials for exploiting such induced storage to gain greater flexibility with integrated regulator operation.

CONTENT

. Section 2 contains findings, conclusions, recommendations and identification of related field research needs.

. Section 3 includes the results from analyses of a conventional interceptor system in Montreal, Quebec, Canada, on the limitations and advantages of integrated regulator control.

. Section 4 briefly explores implications in the provision of induced in-line storage for further enhancing integrated regulator control.

. Section 5 is an introduction to digital recording weather radar for non-meteorologists and includes descriptions of newly available rainfall tracking, measuring and predicting capabilities. Also considered are other engineering uses for radar-generated rainfall data, in particular the resolution of relationships between depths at a reference point raingage and the associated mean rainfalls on discrete urban drainage catchments.

. Section 6 features metropolitan flood warning system development in the Denver, Colorado, area, and describes programs which are pointed towards development of such a capability nationally.

AUTOMATIC OPERATIONAL CONTROL

Before embarking on the findings from this study, it is important to define relevant general aspects of automatic operational control. Levels of control are differentiated, reasons for considering some form of automatic control are reviewed, and objectives of automation are examined.

Levels of Automation(2)

Operational control in urban water resources management spans a spectrum ranging between monitoring and complete, or "hands off," automatic control. While a number of levels of development, each with several variations, could be delineated, three distinct levels can be defined: system monitoring; remote supervisory control; and automatic control. Advances in control capability for urban water resources have mostly evolved from systems for monitoring field variables.

Components of monitoring systems are represented in Figure 1. Not all elements shown are included in all monitoring systems. An example is "on-site variables display" for checking for fidelity of instrument response, instrument malfunction, etc., at individual instrument sites. In the absence of this feature, instruments can be checked by maintenance personnel only by using auxiliary communication (radio or telephone) with the monitoring center. The simpler monitoring systems feature only data logging, visual display charting, and warning and alarm displaying. Some kind of computer capacity is required for "data analysis," but this can be done off-line. Completely missing is any overt field control function. Some form of monitoring system has been deployed for all types of urban water resources systems, including combined sewer systems.

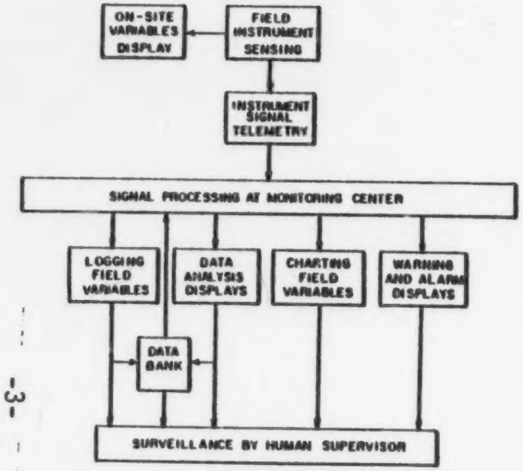
ON-SITE VARIABLES DISPLAY
FIELD INSTRUMENT SENSING
INSTRUMENT SIGNAL TELEMETRY
SIGNAL PROCESSING AT MONITORING CENTER
LOGGING FIELD VARIABLES
DATA ANALYSIS DISPLAYS
CHARTING FIELD VARIABLES
WARNING AND ALARM DISPLAYS
DATA BANK
SURVEILLANCE BY HUMAN SUPERVISOR

FIGURE 1- MONITORING COMPONENTS(2)

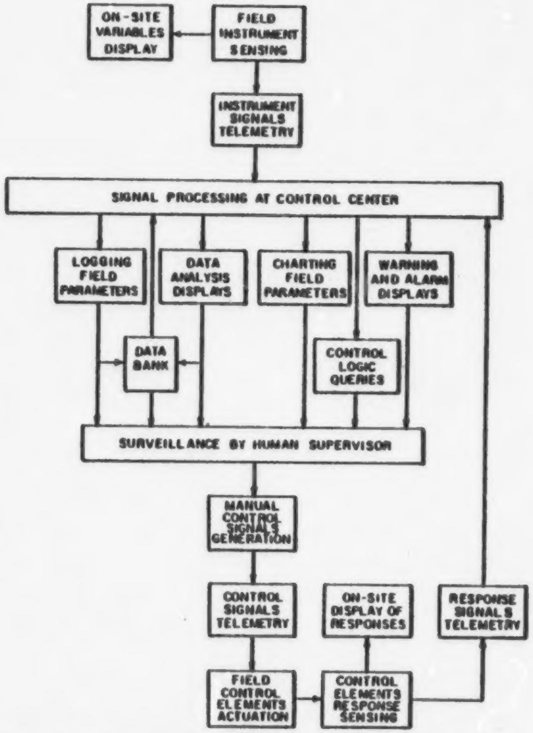
ON-SITE VARIABLES DISPLAY
FIELD INSTRUMENT SENSING
INSTRUMENT SIGNALS TELEMETRY
SIGNAL PROCESSING AT CONTROL CENTER
LOGGING FIELD PARAMETERS
DATA ANALYSIS DISPLAYS
CHARTING FIELD PARAMETERS
WARNING AND ALARM DISPLAYS
DATA BANK
CONTROL LOGIC QUERIES
SURVEILLANCE BY HUMAN SUPERVISOR
MANUAL CONTROL SIGNALS GENERATION
CONTROL SIGNALS TELEMETRY
ON-SITE DISPLAY OF RESPONSES
RESPONSE SIGNALS TELEMETRY
FIELD CONTROL ELEMENTS ACTUATION
CONTROL ELEMENTS RESPONSE SENSING

FIGURE 2-REMOTE SUPERVISORY CONTROL COMPONENTS(2)

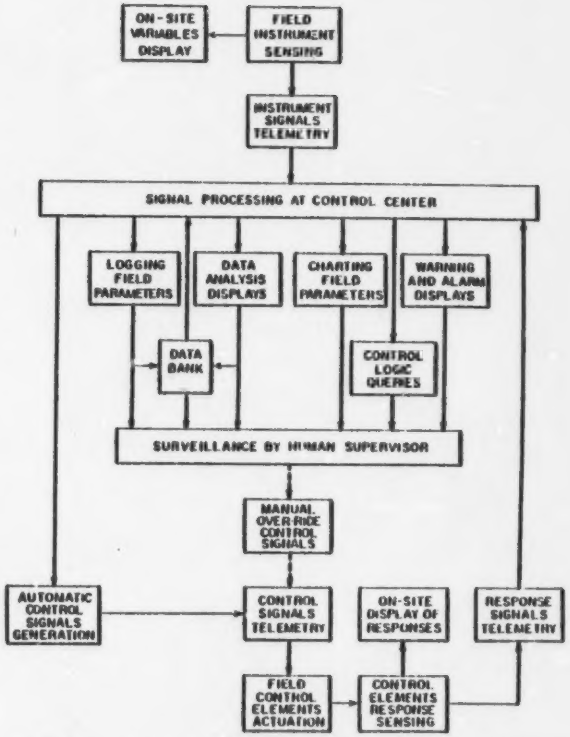
ON-SITE VARIABLES DISPLAY
FIELD INSTRUMENT SENSING
INSTRUMENT SIGNALS TELEMETRY
SIGNAL PROCESSING AT CONTROL CENTER
LOGGING FIELD PARAMETERS
DATA ANALYSIS DISPLAYS
CHARTING FIELD PARAMETERS
WARNING AND ALARM DISPLAYS
DATA BANK
CONTROL LOGIC QUERIES
SURVEILLANCE BY HUMAN SUPERVISOR
MANUAL OVER-RIDE CONTROL SIGNALS
AUTOMATIC CONTROL SIGNALS GENERATION
CONTROL SIGNALS TELEMETRY
ON-SITE DISPLAY OF RESPONSES
RESPONSE SIGNALS TELEMETRY
FIELD CONTROL ELEMENTS ACTUATION
CONTROL ELEMENTS RESPONSE SENSING

FIGURE 3-AUTOMATIC OPERATIONAL CONTROL COMPONENTS(2)

An advanced form of remote supervisory control is represented in Figure 2, which is the content of Figure 1 plus some control features. "Control logic queries" refers to supervisor interrogation of computer-programmed control logic, which can range from elaborate algorithms incorporating prototype response simulation through simple retrieval of command alternatives stored in the computer memory. As is the situation for "data analysis," computer access can be off-line. Actuation of field control elements is performed remotely by manual supervisory command. In simpler systems, control element response to an actuation command can be ascertained indirectly by observing changes in affected field sensor signals. On the other hand, the "response signals telemetry" to the control center in Figure 2 provides direct control-loop feedback, with an opportunity to damp system actuation response instabilities by using guidelines pre-programmed as part of the control logic. Provision of optional "on-site display of responses" facilitates field checking of actuators by maintenance personnel for the same reason given above for "on-site variables display". Although telemetry of instrument, control, and response signals are shown separately in Figure 2, all three could use the same carrier facility. An appropriate analogy to Figure 2 would be flight simulators of the types used for "hands-on" training of airline pilots and astronauts. To be cited are combined sewer system examples.

Components for complete automatic control are shown in Figure 3, which is identical with Figure 2 except for two items: "manual control" has been replaced with "manual over-ride"; and "automatic control signals generation" has been added. The latter is the most challenging and difficult component to develop. Control logic must be greatly expanded, to the extent that the control system can become a full-fledged surrogate for the human supervisor, in what is sometimes termed hands-off operation, with supervisor intervention via manual over-ride only in the event of control system failure or inadequacy. One of the simplest examples of complete automatic control is the auto-pilot employed by aircraft and ships. A more complex example is space-vehicle automatic navigational control. Such a level of complete control has been achieved in urban water resources only in connection with the operation of water treatment and wastewater treatment plants. In a total systems context, the greatest advances have been for water distribution systems, but despite the predominantly deterministic loading of such systems, their complete automation has yet to be achieved. Automation of combined sewer systems is still more complex, due to the completely random nature of their loading by precipitation.

Why Automation?

Combined sewers have the dual functions of removing ephemerally occurring stormwater from urban surfaces and conveying wastewater on a perennial basis. Conduit size is governed by storm drainage requirements, capacity requirements for wastewater being comparatively small. During dry weather, the continuously flowing wastewater is diverted near the combined sewer outfall by means of a regulating device which directs it to the wastewater treatment plant via an interceptor sewer. Large storm flows are much too great to be accommodated by interceptors, and much of the wastewater burden overflows through the outfall to receiving waters when rainstorms are heavy and prolonged. At the same time, sludge and debris that have been stranded during relatively low rates of flow in preceding dry-weather periods are scoured from the laterals and trunk sewers of combined systems and are lifted or otherwise transported by the augmented flows and eventually discharged to receiving waters. Receiving water loading from combined sewer systems thereby includes pollutants washed off the land surface, as for separate storm sewer systems, plus pollutants contained in wastewaters.

In the extreme, the solution to the problem of abating pollution from combined sewer overflows is the treatment of all such flows prior to their release into receiving waters. Outflow surface-water hydrographs of combined sewer catchments exhibit very large peaks, on the order of two or more times those of equivalent non-sewered areas. Capturing, transporting and treating all potential overflows, unattenuated, would require gigantic transport sewers, pumping stations and treatment facilities, all of which would be used less than on the order of three hours a day, on the average, over a typical year. Furthermore, there would be periods running into several weeks or even months where overflow prevention works would not be operated at all, because of little or no precipitation. Therefore, schemes for system-wide control of potential overflows have mostly incorporated some form of auxiliary storage for the purpose of attenuating sudden inflows to collection and treatment facilities, with the objective of scaling down the size of such facilities to reasonable and manageable proportions.

The complexity added by converting a facility with simple gravity flow into a multiple-component interacting scheme, where practically instantaneous response to flow incidences must be made, requires incorporation of some degree of automatic operational control. In addition, automatic control has a potential for permitting the manipulation of dispersed storage capacities for the purpose of maximizing the effective use of their collectively available volumes, and the diversion of otherwise uncontainable releases to lower impact receiving water reaches, by taking advantage of the areal non-uniformity of rainfall over large combined sewer jurisdictions.

Automation Objectives

While no explicit criteria for abatement of pollution from combined sewer overflows have been defined to date, possibilities most often considered are reduction in number of overflows, or reduction in volume of overflows, or preclusion or reduction of the "first flush" of overflows, or reduction of overflow impact on receiving waters, or some combination of these. Because the abatement objective is ultimately the reduction of overflow impact on receiving waters, exclusive use of any other criterion is necessarily an indirect means for achieving that objective.

Discussion will now center on the use of in-system detention storage vis-à-vis automatic control for abatement of pollution from combined sewer overflows. Massive use of such storage is included in the plan being implemented in Chicago, which includes a number of very large tunnels well below ground level and large surface storage reservoirs.(3,4) More modest but still substantial new storage is being added to the San Francisco system, where near-surface, covered collection canals are being used(5) instead of some of the numerous distributed storage basins considered earlier.(6)

The plan being implemented in San Francisco represents the exclusive instance where complete automatic control capability is being sought. In a cooperative project with the City, Colorado State University has explored the possible application of operations research methods to achieve that capability.(5,7) At this juncture, it is important to point out that there are fundamentally two distinctive modes of automatic control, reactive and predictive. The reactive mode refers to the manipulation of facilities in response to the actual occurrence of a rainstorm, as the storm progresses over the affected jurisdiction. The predictive mode refers to the anticipation of how facilities should be handled just prior to the beginning of a rainstorm, and blends with the reactive mode once rainfall on the affected jurisdiction commences, but the predictive feature is retained until the cessation of incipient rainfall. San Francisco is attempting to develop just such a predictive capability.(8) Of particular interest is an intention to investigate alternative rainfall prediction approaches using improved or expanded data acquisition networks and to perform a preliminary investigation of the merits of using radar plus calibrating raingages as part of the future automated combined sewer system.

Achievement of "hands-off," or complete, or closed-loop, automatic control of combined sewer systems in a predictive mode will require the interfacing of a storm prediction capability with models that simulate the important hydrologic and hydraulic behavioral characteristics of catchments, in groups and collectively, with the whole integrated with decision-algorithms reflecting system performance criteria. All this must be effectuated in a real-time context, with shifts in tactics during a storm required in as short an interval as fifteen minutes. Storm prediction capabilities using digital recording radar are described in Section 5 of this report.

The almost complete capture of all potential overflows sought in the major system modifications being implemented in Chicago and San Francisco will be very expensive, mostly because of the substantial new transport and storage facilities that are required to meet such an ambitious pollution abatement goal. Section 3 will deal with measures that address much lesser goals and for which, as a result, implementation is, or would be, a fraction of the cost of major system modifications.

Shown in simplified form in Figure 4 are the essential elements of a dynamic combined sewer-regulator-interceptor diversion structure. Under normal operation, when the collector flow (C) is no greater than the rate permitted through the regulator gate (R), all of (C) enters the interceptor. When (C) exceeds (R), an overflow (O) occurs. (Regulator actuation criteria will be discussed subsequently). If a movable gate, G, is added downstream from the point of regulator diversion, it is possible to pond (C) by exploiting the otherwise temporarily unused ambient storage in the existing trunk sewer outfall as well as perhaps that in tributary sewers upstream. By operating the regulator gate at the same time, such that as much collector flow as possible would be diverted to the interceptor, the resulting maximum use of

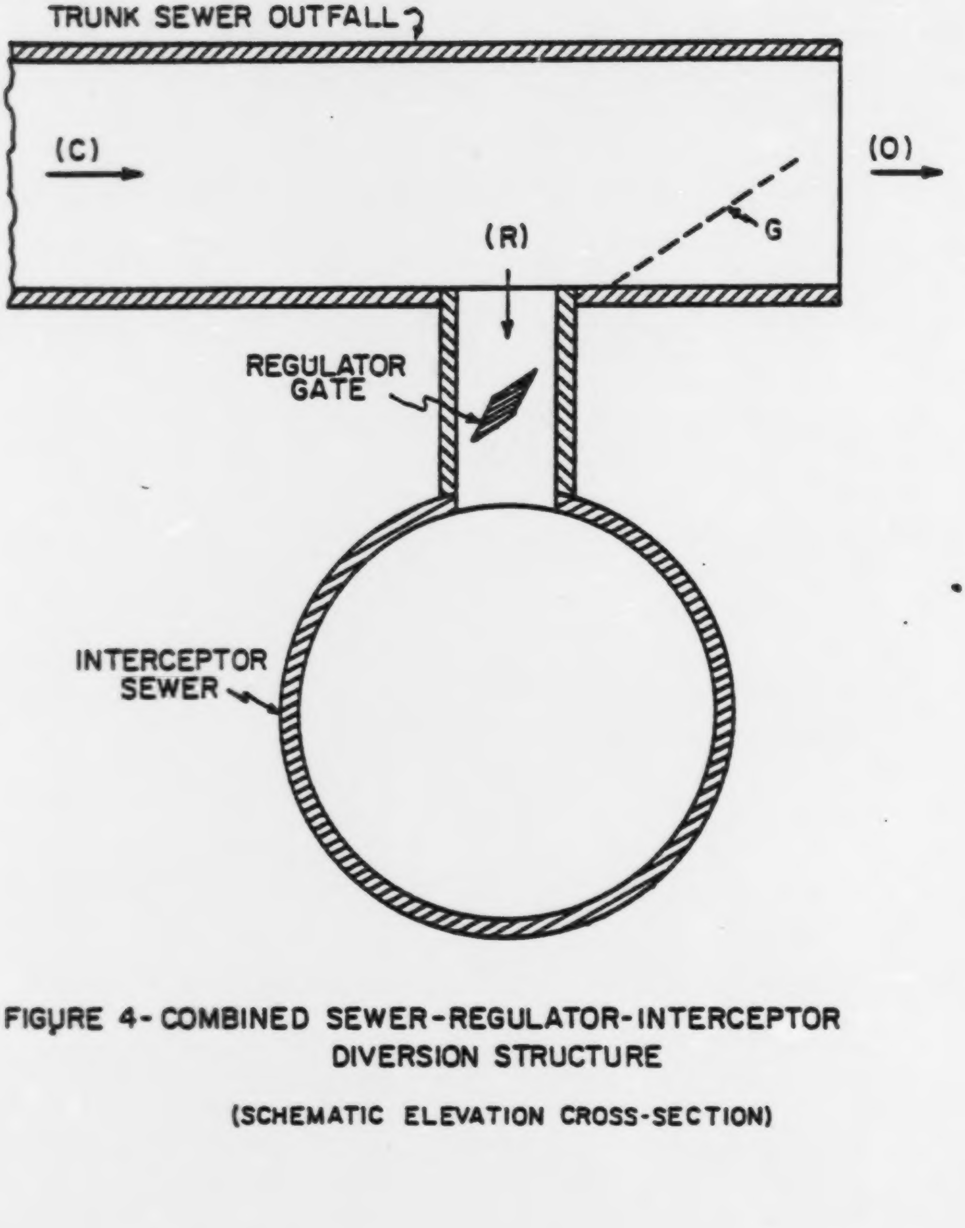
TRUNK SEWER OUTFALL
(C)
(O)
(R)
G
REGULATOR GATE
INTERCEPTOR SEWER

FIGURE 4- COMBINED SEWER-REGULATOR-INTERCEPTOR DIVERSION STRUCTURE

(SCHEMATIC ELEVATION CROSS-SECTION)

interceptor storage and ambient collector storage would lead to fewer or less voluminous overflows over a year, or would permit diversion of much first flush pollutants to the interceptor over a year. This would require joint automatic operation of the regulator gate and the outfall gate. By shifting oversight of actuation to a control center, some degree of supervisory control (Figure 2) could be achieved, and there would be possibilities for even more efficient overall system management through the exploitation of system interactions by integrating the performance of all regulators in the system. This concept was the foundation for control systems developed in Minneapolis-St. Paul,(9) Detroit(10) and Seattle.(11) More will be said about these cases in Section 4, in connection with potentials for exploiting in-line storage.

ACKNOWLEDGMENTS

This study was conducted for the ASCE Urban Water Resources Research Council by its full-time operating arm, the ASCE Urban Water Resources Research Program. After a public service spanning fourteen years it was necessary to terminate the Program just as this study was being completed. Mr. M. B. McPherson was Program Director and principal investigator of this study, and wrote the text of this report. The Council received substantial assistance in the study from: Ecole Polytechnique, University of Montreal; Montreal Urban Community; Urban Drainage and Flood Control District, Denver; meteorologists of MIT, McGill University, Illinois State Water Survey, National Weather Service and Environmental Research Laboratory of NOAA, and Space Science and Engineering Center of the University of Wisconsin; City of Milwaukee; Melbourne and Metropolitan Board of Works; Seattle Metro; Metropolitan Sanitary District of Greater Chicago; City of San Francisco; Milwaukee Metropolitan Sewerage District; and City of Detroit. Acknowledgments to individuals are included throughout the text as appropriate. The Storm and Combined Sewer Section at Edison, New Jersey, of the USEPA Municipal Environmental Research Laboratory was very helpful in facilitating the study, particularly the Section's Mr. Douglas C. Ammon, Project Officer. ASCE Council oversight was provided by the ASCE Program's Steering Committee: S. W. Jens (Chairman); W. C. Ackermann; J. C. Geyer; N. S. Grigg, C. F. Izzard; D. E. Jones, Jr.; and L. S. Tucker. Last but not least, Mrs. Richard P. Symmes of Marblehead, Mass., served as administrative assistant for the study and typed all study documents including this report.

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SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Integrated Regulator Operation

Automatic dynamic combined sewer system regulators are conventionally operated under a local control mode wherein each regulator is actuated only in response to the stage of flow in the interceptor in its immediate vicinity. Explored in Montreal (Section 3) was the feasibility of integrating the operation of all regulators on a given interceptor by means of a centralized automatic control scheme when no in-line or other in-system storage is available.

No advantage over local automatic dynamic regulator control can be accrued by integrating the operation of regulators on a given interceptor unless flowrates can be predicted adequately in advance. The minimum necessary lead time is equal to the flow travel time from the regulator furthest upstream in the interceptor to the one furthest downstream that are to be operated collectively.

Even if flowrate prediction is employed, no advantage over conventional local regulator operation can be accrued by integrating the operation of regulators on a given interceptor unless the diversion of flows by the regulators in the form of overflows is programmed so as to minimize overflows at one or more particular regulators, or so as to minimize overflows at some time period over the duration of storm events (e.g., during the "first flush"), or both. That is, employment of a weighting function is also required.

Even if both flowrate prediction and a weighting function are used, the total volume of overflows for an event will not be changed. That is, even though overflows are precluded or reduced at designated outlets or for designated time periods or both, the total volume of overflows for an event will remain unchanged. However, when a pollutant characteristic that diminishes in concentration over time is considered, it is possible to reduce emissions at designated outfalls by using integrated regulator operation, again provided that flowrate prediction and a weighting function are employed.

Preliminary tests indicate that a storm moving across the tributary catchments of an interceptor in the direction of flow can increase the volume of overflows over the amount for a presumed stationary storm. While not tested, it is expected that storm movement in the opposite direction would result in a diminishment in the volume of overflows over that for a presumed stationary storm.

As would be expected, reductions in overflows anticipated via integrated regulator operation may be highly system-specific. The potential for overflow reduction in the Montreal case studied so far appears to be marginal for a "first flush" pollutant reduction, but very promising for pollutant reductions at designated outfalls. There will probably be more attractive possibilities elsewhere, as well as situations where no real improvement can be expected.

In-Line Storage

Viewed as a particularly attractive means for reducing combined sewer overflows, in-line storage exploits the "unused" volume in interceptors and trunk sewers. Such temporary storage can be induced by manipulating existing and/or added flow control devices. In-line storage has been a control component of some central dispatching systems designed for supervisory operation.

Cursory comparison of potentially exploitable collector and outfall sewer in-line storage in Montreal and Milwaukee with that already exploited in Seattle revealed two important departures. The volume of exploitable in-line storage inherent in the Seattle combined sewer system is generous compared with that potentially exploitable in Montreal and Milwaukee. The bulk of combined sewer systems are in the northeast and midwest where rainfall intensities and total storm depths are generally higher than in Seattle. As a result, the success in exploiting in-line storage in Seattle should not be casually presumed to be duplicative elsewhere.

Digital Recording Radars

Newly developed capabilities for measuring and predicting rainfall by means of digital recording radars (Section 5) show considerable promise for the effectuation of automated combined sewer system operation and for enhancing metropolitan flood warning systems. Meteorologists have expressed cautious confidence over the reliability of radar measurements and there are important rainfall characteristics with implications in planning and design of urban water resources facilities that may be explicated in the near future from such measurements. With regard to combined sewer operations, of singular importance is the existence of two rainfall prediction schemes that permit estimation of rainfall over discrete catchments up to two or three hours in advance. Because the range of suitable weather radars is about 125-miles (200-km), and the use of a telemetered raingage network covering that range is not realistic, the only means for providing the rainfall prediction required for automation of conventional combined sewer systems with long interceptors is digital recording radar.

Metropolitan Flood Warning

Flash flood warning systems are being installed in metropolitan Denver on a basin by basin accretion basis (Section 6). There appear to be attractive advantages to the addition of rainfall and runoff prediction capabilities to existing real-time rainfall and stream-stage observations. Rainfall forecasts based on satellite imagery show considerable promise in filling the prediction time gap between twice-daily synoptic forecasts and the two to three hour lead time provided by digital recording radars, for both flood warning and combined sewer system operation applications. Flash-flood warning field development over the next few years in the Denver area should not only greatly strengthen that capability but should also provide important insights for automation of combined sewer system operations.

RECOMMENDATIONS

Completely unknown is the reliability of rainfall prediction through catchment hydrology through combined sewer system dynamics in terms of receiving water pollution impacts. While it will be some time before this analytical chain can be adequately tested, much exploratory work remains to be done. It is hoped that tentative plans will be implemented in certain jurisdictions to determine the extent to which rainfall and runoff predictions can enhance combined sewer operations. Such explorations are in the national interest and are of international curiosity, because they would deal with the cutting edge of available technology. Findings from explorations of the adaption of predictive capabilities to metropolitan flood warning should be examined carefully for their potential transfer to combined sewer system applications.

There appear to be limitations in the extent to which overflows from conventional combined sewer interceptor systems can be minimized without the addition of storage. Because the addition of in-system storage reservoirs is expensive compared with the inducement of storage in collector and outfall sewers, it is important that the degree of availability of the latter be sampled nationally as soon as possible.

In the meanwhile, improved understanding of the operation of individual combined sewer systems might be attained by observing the qualitative movement and intensity of storms using an inexpensive display device of the type employed in Denver (Section 6) wherever a suitable National Weather Service radar scanning area encompasses the affected jurisdiction. Such surveillance would be enhanced by comparing areal implications from radar with data from the local raingage network, even if done after the fact. Also, this modest commitment could be an excellent precursor for later adoption of a digital recording radar capability.

SECTION 3

AUTOMATED COMBINED SEWER SYSTEMS

by Communauté Urbaine de Montréal
and Ecole Polytechnique de Montréal

INTRODUCTION

This Section draws on information developed in Montreal, Quebec, Canada. Principal contributors have been Ecole Polytechnique (E.P.) of the University of Montreal, and the Montreal Urban Community (Communauté Urbaine de Montréal) (C.U.M.). Interaction between the Urban Water Resources Research Group at E.P. and the technical staff at the C.U.M. is facilitated by a written agreement for cooperation and collaboration in urban water resources research, development and training. The C.U.M. is a metropolitan multiple-purpose special district that includes among its responsibilities, mainly for the island of Montreal, the collection of all wastewaters and their treatment by the design, construction and eventual operation of the required interceptors and treatment plant. The C.U.M., because the required hardware is included in all of its regulators, is seeking through different levels of development the complete automation of its interceptor systems. As a service to the C.U.M. in this connection, E.P. completed in 1978 an exploratory study of the feasibility of storm tracking for automatic control of combined sewer systems.(1)

Contributions to this Section by the C.U.M. were mostly via Mr. H. N. Nguyen Van and Mr. M. Osseyrane. Contributions by E.P. were mostly via Mr. M. B. McPherson, who was a part-time invited professor through 1979, and Professor Gilles Patry. Mr. Guy Paquin and Mr. Denis Burroughs of C.U.M. and Mr. Gilles Marchi of E.P. provided important technical assistence to both groups.

REGULATORS

There are several major types of regulator devices presently in use in North America, broadly classified as either static or dynamic regulators.(2) Interest here is exclusively on automatic dynamic regulators, whether they have motor-operated or hydraulically-operated gates. Low weirs are commonly installed across the bottom of the outfall sewer, just downstream from the regulator diversion area, to facilitate entry of flow into the regulator by-pass. When movable gates are added near the exit of an outfall (G in Figure 4, Section 1), any such weirs are usually removed because they are replaced by the new gates. To be described are findings from studies of a Montreal system, where deep interceptors have made it possible to use drop-type chutes to convey flows from collectors to interceptors without having to include diversion weirs. Lastly, while regulators can be actuated by set-point stages in collector sewers or interceptor sewers or both, automatically controlled regulators should be responsive to interceptor sewer set-point stages, where the objective is to maximize diversion of wet-weather flows to treatment while capturing all dry-weather flow.

One estimate is that a capacity of 80 to 160 times the peak dry-weather flow would be required in interceptors in order to prevent wet-weather overflows.(3) The hydraulic capacity of interceptors should be at least 2 to 4 times the average dry-weather flow for the design year "if overflows of raw sewage into watercourses are to be prevented during dry weather,"(3) with the lesser minimum being applicable to large interceptors. It is generally believed that many large interceptors can carry a stormwater burden at least equal to the average dry-weather flow. However, it is obvious that combined sewage from only a limited number of storms can be completely diverted to an interceptor. That is, storage available in interceptors to accommodate wet-weather flows is extremely limited, and this is the reason why recourse has been made to induced in-line storage in collectors in Minneapolis-St. Paul, Seattle and Detroit. While no in-line storage is at issue in this Section, that subject is reviewed in Section 4.

Automatically controlled regulators are being installed in the Montreal system. Microcomputers at each regulator will be used to actuate that regulator's diversion gate, which will be operated to maximize effective use of interceptor capacity with free-surface flow in the interceptor (i.e., no surcharging). Regulator facilities are to be monitored remotely at an operations center, taking advantage of a minicomputer dedicated exclusively to the operation of the interceptors. A question arose on the possibility of reducing overflows by means of conjoint, integrated operation of regulators. That is, what reduction in overflows can be expected when a monitoring system (Figure 1, page 1-3) is transformed into an automatic control system (Figure 3, page 1-3)? The remainder of this Section summarizes what had been learned from the various studies that had been made in Montreal by June, 1980, in an attempt to answer that question. Consideration has been restricted to the incidence, location and timing of overflows, without regard to receiving water impacts. The latter will be addressed in subsequent Montreal studies. Of interest at that time will be a planning model developed in Toronto(4) that takes more metropolitan loading considerations into account than were included in the studies reported herein.

NEED FOR PREDICTION

In the Montreal studies, independent operation of regulators has been termed local dominion control, or simply "local control," and conjoint operation of regulators has been termed "integrated control". At the beginning of the initial study in 1979, the importance of a predictive mode versus a reactive mode was explored for integrated control versus local control. This subsection draws upon the conclusions reached early in that study, which focused on the perfection of an algorithm for minimizing overflows for integrated control.(5)

Consideration will be restricted to time-lag routing with the interceptor flow velocity held constant at 5-feet/second (1.5 m/sec.). Figure 5 is a schematic representation of the hypothetical case to be considered. The length of interceptor between each pair of regulators is taken as 3,000-feet (900-m), with a resultant regulator-to-regulator travel time of 10 minutes. Adopting a time step, Δt, of 5-minutes, the 10-minute travel time between each pair of regulators is thus 2 Δt. Collector flow (C), regulator diversion (R) and overflow (O) are as already shown in Figure 4, page 1-7. Flow in the interceptor is designated as (I) in Figure 5, where the 60-minute hydrographs of C-values that are to be routed through the interceptor are also shown.

For Regulator Number n at time t,

$$(R_n)_t = (C_n)_t - (O_n)_t$$

and, for any time t the flow in the interceptor (I_n) below each regulator delivering (R_n) to it is:

$$(I_1)_t = (R_1)_t \ ;$$

$$(I_2)_t = (I_1)_{t - 2\Delta t} + (R_2)_t \ ;$$

$$(I_3)_t = (I_1)_{t - 4\Delta t} + (I_2)_{t - 2\Delta t} + (R_3)_t \ ;$$

$$(I_4)_t = (I_1)_{t - 6\Delta t} + (I_2)_{t - 4\Delta t} + (I_3)_{t - 2\Delta t} + (R_4)_t \ ; \text{ and}$$

$$(I_5)_t = (I_1)_{t - 8\Delta t} + (I_2)_{t - 6\Delta t} + (I_3)_{t - 4\Delta t} + (I_4)_{t - 2\Delta t} + (R_5)_t \ .$$

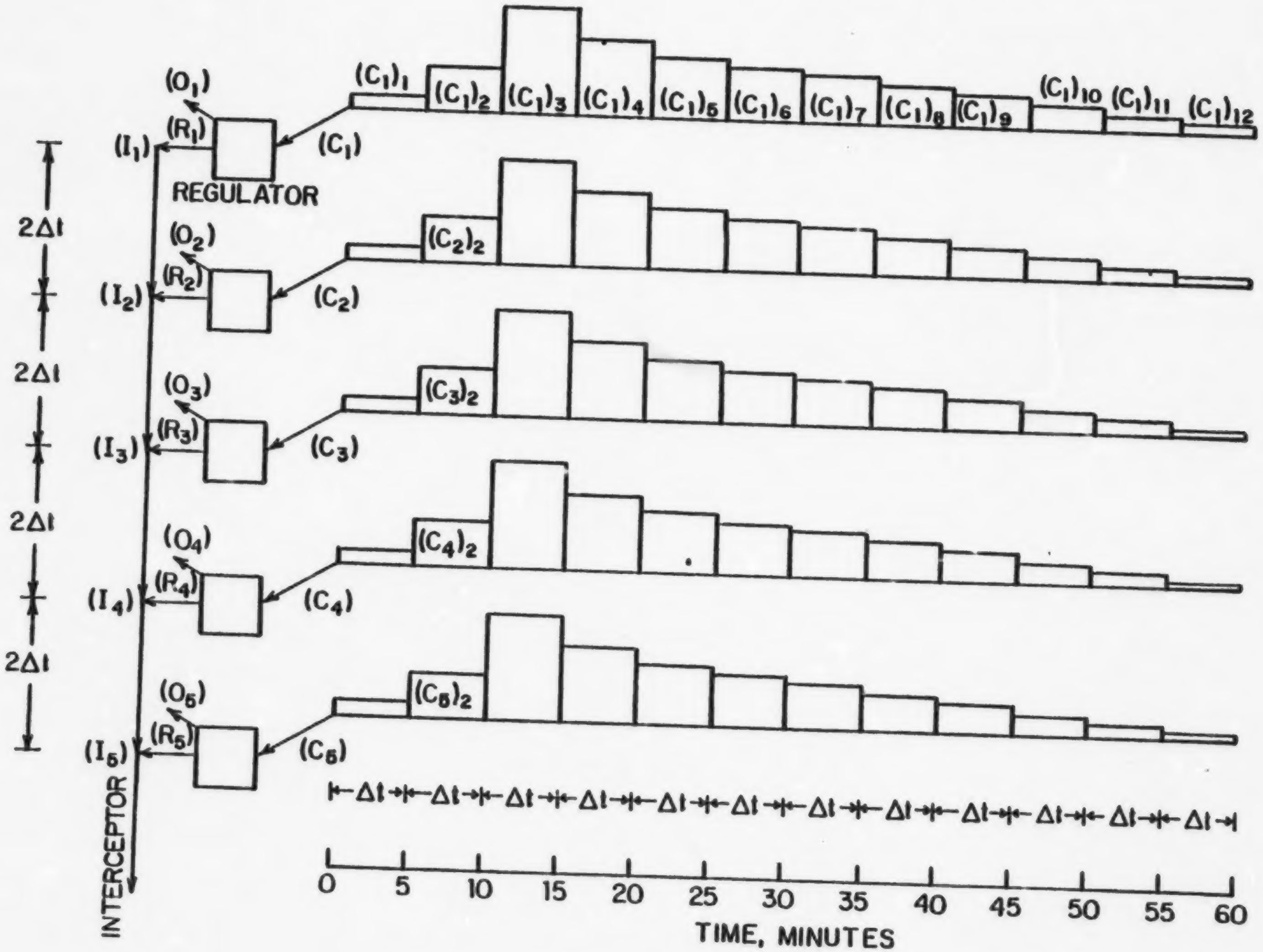
Designating the regulator throughput hydraulic capacity as $(R_n)_{max}$ and interceptor hydraulic capacity immediately downstream from a given regulator facility as $(I_n)_{max}$:

$$(R_n) \leqq (R_n)_{max}$$

and

$$(I_n) \leqq (I_n)_{max} \ .$$

Consider the collector flows (C), alone, entered in Table 1. The solid lines with arrows connect the earliest values of (C) that have a bearing on the interceptor flow accumulated downstream from Regulator Number 5, (I_5). Note that a value for $(C_1)_1$ would have to be estimated at least 40 minutes before it actually occurred in order to be able to manipulate it to any advantage of $(I_5)_9$. Similarly, minimum prediction periods required for manipulation of the other regulators to have any beneficial effect on (I_5) would be: 30 minutes for $(C_2)_1$ to affect $(I_5)_7$; 20 minutes for $(C_3)_1$ to affect $(I_5)_5$; and 10 minutes for $(C_4)_1$ to affect $(I_5)_3$. In order to integrate the performance of these five regulators, a predictive capability would be required. This would be true even if (R_n) was less than (C_n), as would be the situation with the occurrence of an overflow.


(O₁)
(R₁)
(I₁)
REGULATOR
(C₁)
(C₁)₁
(C₁)₂
(C₁)₃
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(C₁)₅
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(C₁)₁₁
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(O₂)
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(R₅)
(I₅)
(C₅)
(C₅)₂
2Δt
2Δt
2Δt
2Δt
INTERCEPTOR
Δt
0
5
10
15
20
25
30
35
40
45
50
55
60
TIME, MINUTES

FIGURE 5-EXAMPLE OF TIME-LAG ROUTING

TABLE 1

SPATIALLY UNIFORM RAINFALL OVER CATCHMENTS

INTERVAL, t	TIME, Minutes	COLLECTOR FLOWS ABOVE REGULATORS				
		No. 1	No. 2	No. 3	No. 4	No. 5
	0					
1		$(C_1)_1$	$(C_2)_1$	$(C_3)_1$	$(C_4)_1$	$(C_5)_1$
	5					
2		$(C_1)_2$	$(C_2)_2$	$(C_3)_2$	$(C_4)_2$	$(C_5)_2$
	10					
3		$(C_1)_3$	→ $(C_2)_3$	$(C_3)_3$	$(C_4)_3$	$(C_5)_3$
	15					
4		$(C_1)_4$	$(C_2)_4$	$(C_3)_4$	$(C_4)_4$	$(C_5)_4$
	20					
5		$(C_1)_5$	$(C_2)_5$	→ $(C_3)_5$	$(C_4)_5$	$(C_5)_5$
	25					
6		$(C_1)_6$	$(C_2)_6$	$(C_3)_6$	$(C_4)_6$	$(C_5)_6$
	30					
7		$(C_1)_7$	$(C_2)_7$	$(C_3)_7$	→ $(C_4)_7$	$(C_5)_7$
	35					
8		$(C_1)_8$	$(C_2)_8$	$(C_3)_8$	$(C_4)_8$	$(C_5)_8$
	40					
9		$(C_1)_9$	$(C_2)_9$	$(C_3)_9$	$(C_4)_9$	→ $(C_5)_9$
	45					
10		$(C_1)_{10}$	$(C_2)_{10}$	$(C_3)_{10}$	$(C_4)_{10}$	$(C_5)_{10}$
	50					
11		$(C_1)_{11}$	$(C_2)_{11}$	$(C_3)_{11}$	$(C_4)_{11}$	$(C_5)_{11}$
	55					
12		$(C_1)_{12}$	$(C_2)_{12}$	$(C_3)_{12}$	$(C_4)_{12}$	$(C_5)_{12}$
	60					

Shown in Table 2 are the collector flows for the same storm, but with the storm moving across the tributary catchments at a speed of 7-mph in the direction of flow in the interceptor. As for the case of a spatially uniform storm in Table 1, predictive capability is required for any advantage to accrue to downstream interceptor reaches through integrated control. Of course, earlier values of (I_5) are affected by the downstream storm movement, such as (C_1), on $(I_5)_5$ versus its connection with $(I_5)_9$ in Table 1. In either case, a prediction lead time of at least 40 minutes is required.

Shown in Table 3 are the collector flows for the same storm again but with it moving across the catchments at a speed of 7-mph in the direction opposite to that of the flow in the interceptor. There would be no interaction of Regulator Number 5 with Regulator Number 1 under integrated control. However, a value of $(C_1)_1$ would have to be estimated at least 30 minutes in advance so its impact on $(I_4)_{10}$ could be weighed.

Thunderstorms are the cause of numerous major overflows and thunderstorm movement is nearer to 30-mph than the 7-mph used above. A velocity of 5-feet/second in the interceptor and an inter-regulator distance of 3,000-feet are within the realms of actual systems. That is, for actual systems and actual thunderstorms there should be less difference between prediction requirements for upstream versus downstream storm movement than suggested by the examples given here. On the other hand, a speed of storm travel of 7-mph would not be unrealistic for much of cyclonic storm rainfall. Unfortunately, prior studies of automatic control have failed to segregate system performance by storm type or season of the year. There is a related rainfall distribution enigma. Whereas frontal storm rainfall is rather uniformly distributed over large areas, thunderstorm rainfall is commonly concentrated over areas on the order of a few square miles in size due to the cellular structure of such storms.

Capabilities will be cited in Section 5 for predicting rainfalls on specified catchments for upwards of two to three hours in advance. For an interceptor flow velocity of 5-feet/second, this lead time translates into an interceptor length of 7-miles to 10-miles, a length not uncommon in larger cities. The newer predictive capabilities thus appear to be suited to combined sewer system automation uses, although there would be cases where even longer lead times would be desired. The preceding presumes that interceptor travel time will govern minimum prediction period requirements.

NEED FOR WEIGHTING FUNCTIONS

Consideration hereinafter will be restricted to predictive situations, presuming that all $(C_n)_t$ can be estimated up to two hours before the incidence of the causative rainfall on their respective catchments. The next question deals with the presumed superiority of predictive, integrated control over non-predictive local control. That is, returning to Table 1, it will now be assumed that estimates of all $(C_n)_t$ values would have been available adequately in advance of their actual occurrence. Exploration of several scenarios will give some insight into what might and what might not be done.

TABLE 2

STORM MOVING OVER CATCHMENTS IN DOWNSTREAM DIRECTION OF INTERCEPTOR

INTERVAL, t	TIME, Minutes	COLLECTOR FLOWS ABOVE REGULATORS				
		No. 1	No. 2	No. 3	No. 4	No. 5
	0					
1		$(C_1)_1$ —				
	5					
2		$(C_1)_2$	$(C_2)_1$			
	10					
3		$(C_1)_3$	→ $(C_2)_2$ —	$(C_3)_1$		
	15					
4		$(C_1)_4$	$(C_2)_3$	$(C_3)_2$	$(C_4)_1$	
	20					
5		$(C_1)_5$	$(C_2)_4$	→ $(C_3)_3$ —	$(C_4)_2$	$(C_5)_1$
	25					
6		$(C_1)_6$	$(C_2)_5$	$(C_3)_4$	$(C_4)_3$	$(C_5)_2$
	30					
7		$(C_1)_7$	$(C_2)_6$	$(C_3)_5$	→ $(C_4)_4$ —	$(C_5)_3$
	35					
8		$(C_1)_8$	$(C_2)_7$	$(C_3)_6$	$(C_4)_5$	$(C_5)_4$
	40					
9		$(C_1)_9$	$(C_2)_8$	$(C_3)_7$	$(C_4)_6$	→ $(C_5)_5$
	45					
10		$(C_1)_{10}$	$(C_2)_9$	$(C_3)_8$	$(C_4)_7$	$(C_5)_6$
	50					
11		$(C_1)_{11}$	$(C_2)_{10}$	$(C_3)_9$	$(C_4)_8$	$(C_5)_7$
	55					
12		$(C_1)_{12}$	$(C_2)_{11}$	$(C_3)_{10}$	$(C_4)_9$	$(C_5)_8$
	60					
13			$(C_2)_{12}$	$(C_3)_{11}$	$(C_4)_{10}$	$(C_5)_9$
	65					
14				$(C_3)_{12}$	$(C_4)_{11}$	$(C_5)_{10}$
	70					
15					$(C_4)_{12}$	$(C_5)_{11}$
	75					
16						$(C_5)_{12}$
	80					

TABLE 3

STORM MOVING OVER CATCHMENTS IN UPSTREAM DIRECTION OF INTERCEPTOR

INTERVAL, t	TIME, Minutes	COLLECTOR FLOWS ABOVE REGULATORS				
		No. 1	No. 2	No. 3	No. 4	No. 5
	0					
1						$(C_5)_1$
	5					
2					$(C_4)_1$	$(C_5)_2$
	10					
3				$(C_3)_1$	$(C_4)_2$	$(C_5)_3$
	15					
4			$(C_2)_1$	$(C_3)_2$	$(C_4)_3$	$(C_5)_4$
	20					
5		$(C_1)_1$	$(C_2)_2$	$(C_3)_3$	$(C_4)_4$	$(C_5)_5$
	25					
6		$(C_1)_2$	$(C_2)_3$	$(C_3)_4$	$(C_4)_5$	$(C_5)_6$
	30					
7		$(C_1)_3$ →	$(C_2)_4$	$(C_3)_5$	$(C_4)_6$	$(C_5)_7$
	35					
8		$(C_1)_4$	$(C_2)_5$	$(C_3)_6$	$(C_4)_7$	$(C_5)_8$
	40					
9		$(C_1)_5$	$(C_2)_6$	→ $(C_3)_7$	$(C_4)_8$	$(C_5)_9$
	45					
10		$(C_1)_6$	$(C_2)_7$	$(C_3)_8$	$(C_4)_9$	$(C_5)_{10}$
	50					
11		$(C_1)_7$	$(C_2)_8$	$(C_3)_9$	→ $(C_4)_{10}$	$(C_5)_{11}$
	55					
12		$(C_1)_8$	$(C_2)_9$	$(C_3)_{10}$	$(C_4)_{11}$	$(C_5)_{12}$
	60					
13		$(C_1)_9$	$(C_2)_{10}$	$(C_3)_{11}$	$(C_4)_{12}$	→
	65					
14		$(C_1)_{10}$	$(C_2)_{11}$	$(C_3)_{12}$		
	70					
15		$(C_1)_{11}$	$(C_2)_{12}$			
	75					
16		$(C_1)_{12}$				
	80					

Assuming that values of $(C_n)_t$ estimated in advance would indicate for Table 1 that $(C_5)_9 > (R_5)_{max}$, there would then be an overflow $(O_5)_9 = (C_5)_9 - (R_5)_9 = (C_5)_9 - (R_5)_{max}$. This overflow could not be avoided because the maximum hydraulic diversion capacity of Regulator Number 5 was exceeded by $(C_5)_9$. That is, an unavoidable overflow will always result when $(C_n)_t > (R_n)_{max}$, by definition.

When $(C_n)_t \leqq (R_n)_{max}$, the only way that an overflow can occur is when the maximum local interceptor capacity, $(I_n)_{max}$, would nevertheless be exceeded by contributary flows. For local control, the regulator where $(I_n)_{max}$ was being approached would be progressively closed to the extent necessary to hold $(I_n)_t \leqq (I_n)_{max}$. If, during such incremental closing, $(R_n)_t$ became less than $(C_n)_t$ at any regulator, an overflow would occur at that regulator; and this would apply equally to integrated control.

Returning to $(C_5)_9$ in Table 1, if prediction of flow for $(I_5)_9$ indicated a rate that would exceed $(I_5)_{max}$, the only way that $(I_5)_9$ could be reduced below $(I_5)_{max}$ without causing an overflow $(O_5)_9$ would be by reducing one or more of the other associated interceptor flows: $(I_1)_1$, $(I_2)_3$, $(I_3)_5$ and $(I_4)_7$. This could be done only by making $(R_1)_1 < (C_1)_1$ and/or $(R_2)_3 < (C_2)_3$ and/or $(R_3)_5 < (C_3)_5$ and/or $(R_4)_7 < (C_4)_7$, which means that an overflow would occur at any and all those regulators where $(R_n)_t$ was made less than $(C_n)_t$. That is, to preclude an overflow at a downstream regulator requires creating or worsening one or more overflows at regulators upstream. Proceeding up the interceptor, such as to $(I_3)_5$, the same constraint applies, but in that case only to $(I_1)_1$ and/or $(I_2)_3$. (If backwater effects were taken into account, interceptor stages downstream from the stage for $(I_3)_5$ could also be influential).

The argument immediately above would apply even if the storm moved in such a way as to cause the first collector flows to enter the interceptor at its upstream end (Table 2) or at its downstream end (Table 3); and although the magnitudes of the overflows would normally be expected to differ between these two extremes, the number of incidences would not. Preclusion of an overflow at one regulator under these circumstances would merely cause one or more otherwise nonoverflowing regulators to experience an overflow. However, the distribution of the total volume of overflows would be modified, and if the dynamics of interceptor flows were taken into account it is conceivable that the resulting rearranged overflows might be of lesser volume than that of the overflow avoided at the regulator that had been favored. To which regulator stations overflow incidence would be transferred would be random, owing to the low level of persistence of storm paths and storm directions. That is, integrated control would not permit the designation of relief overflow points well in advance of an event. Putting it another way, although storm prediction would be used, the mode of control nevertheless essentially would be reactive for a given storm.

In addition, the preceding characterizations deal only with general conditions that would be associated with the incidence of overflows. Complications arise when some sort of minimization is attempted. For example, there can be multiple combinations of regulator manipulations that can meet a minimum total overflow requirement. That is, several optimum solutions can exist. Each optimum would be attained with a different mix of overflow amounts and locations. In order to obtain a unique optimal solution it is necessary to introduce some sort of bias of preference.

In sum, it appears that, in general, some basis for a bias of preference must be introduced to make a case for integrated over local control when no in-line or other in-system storage can be called upon. This preference could be at least partially introduced by system dynamics, such as is provided by the hydraulic continuum of the motion in the interceptor, or by the variability in the system as it responds to areal and temporal rainfall variations over the total area tributary to the interceptor. Because areal and temporal rainfall variations are random in character and it is not realistic to speculate on the general effects of interceptor flow dynamics, a bias of preference should be attached to decision variables, such as a preferred reach for overflows or a preferred timing for the initiation of overflows. This can be accomplished by attaching a weighting function, w, to the overflows, such as $(w_1O_1)_t$, $(w_2O_2)_t$, etc. For example, large values of w can be used for an upstream reach and low values of w can be used for a downstream reach, and vice versa, in an optimization scheme. Likewise, large values of w can be assigned to all $(w_nO_n)_t$ over the first few time intervals, to reduce the "first flush" of overflows, with low values of w assigned for the remaining time intervals, in an optimization scheme. Precisely these kinds of weighting functions were used in the analysis of an actual system, the results of which are reported in the remainder of this Section.

MONTREAL ISLAND NORTH INTERCEPTOR(5,6)

Shown in Figure 6 is the new North Interceptor of the C.U.M., that will serve more than half of the Island of Montreal. Connections from the combined sewer area are at ten regulators, the numbered dots on Figure 6. Only wastewater will enter the interceptor west of the combined sewer area and the downstream sector to the east is expected to remain undeveloped for some time. Most of the combined sewer area tributary to the North Interceptor is within the City of Montreal, which occupies a central band across the Island from river to river.

For the preliminary findings to be reported, analysis was restricted to the 7.35-mi. (11.8-km) reach between Regulator No. 1 and Regulator No. 10, Table 4. For the analyses to be reported, the dry-weather flow in the interceptor from the separate wastewater tributary area to the west was taken into account in computing the interceptor stage at the Regulator No. 1 site and throughout the study reach. Conditions in the interceptor below Regulator No. 10 were ignored. For all results to be reported, maximum interceptor capacity was restricted throughout to free-surface flow without surcharge, and the objective was to maximize the use of the interceptor within that limit. The design capacity of the North Interceptor in the reach between Regulators Nos. 1 and 10 is 2½ times the dry-weather flow.

Initial Study(5)

Scope of Initial Study -

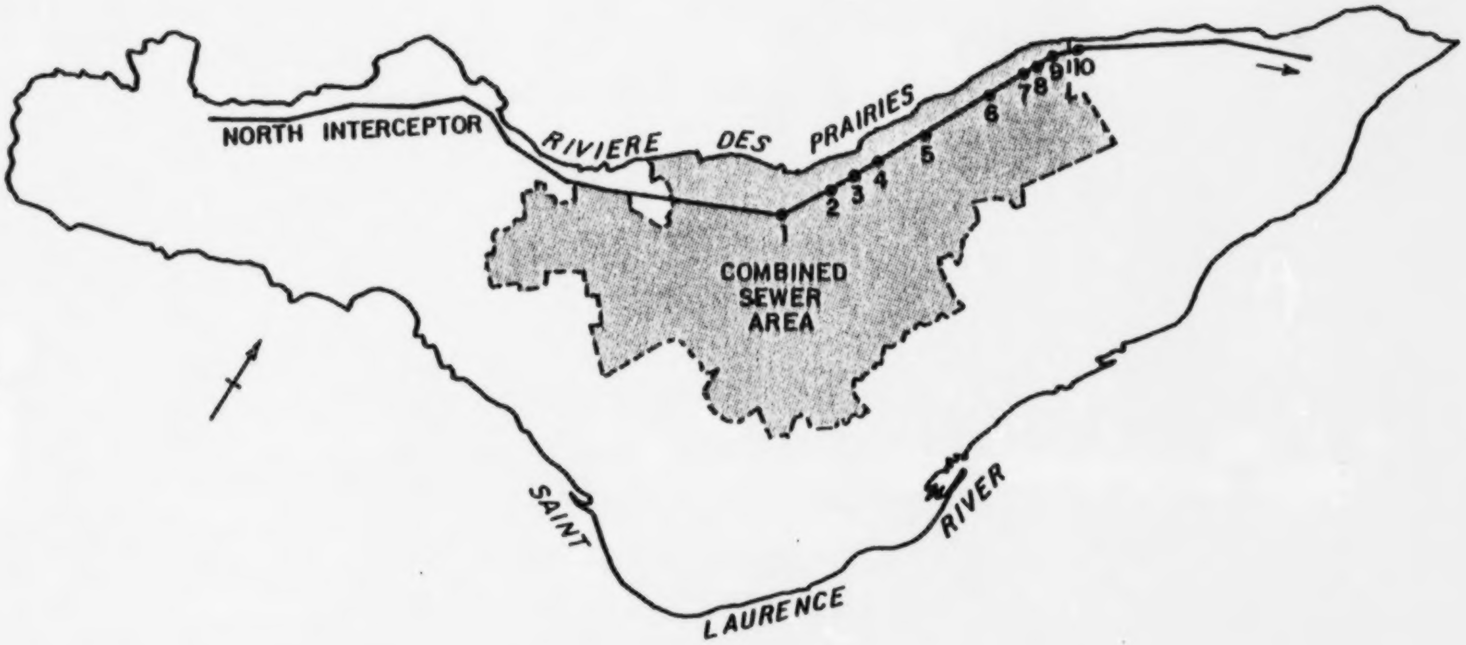
NORTH INTERCEPTOR
RIVIERE DES PRAIRIES
1
2
3
4
5
6
7
8
9
10
COMBINED SEWER AREA
SAINT LAURENCE RIVER

FIGURE 6-ISLAND OF MONTREAL: STUDY AREA REGULATORS ON NORTH INTERCEPTOR AND THEIR TOTAL COMBINED SEWER TRIBUTARY AREA

TABLE 4

NORTH INTERCEPTOR REGULATORS IN STUDY AREA

REGULATOR NUMBER	TRIBUTORY AREA		DISTANCE BETWEEN REGULATORS		CAPACITY OF REGULATOR		CAPACITY OF COLLECTOR AT REGULATOR		TRANSPORT INTERVAL (Δt = 4 min.)
	Acres	Ha	Feet	Meters	cfs	lit./sec.	cfs	lit./sec.	Minutes
1*	9655	3907			600	17000	2960	83750	
			6500	1980					5 Δt
2*	3455	1398			600	17000	2230	62350	
			2300	700					2 Δt
3	816	330			150	4250	250	7100	
			1300	400					1 Δt
4	1643	665			300	8500	950	27050	
			4700	1430					4 Δt
5*	2883	1167			300	8500	1100	31050	
			9200	2800					8 Δt
6	2005	811			300	8500	600	17000	
			6800	2070					6 Δt
7	631	255			300	8500	400	11300	
			2300	700					2 Δt
8	116	47			150	4250	150	4250	
			1300	400					1 Δt
9	362	147			150	4250	400	11300	
			4400	1340					4 Δt
10	1781	721			450	12750	950	26900	
	23347	9448	38800	11820	---	---	---	---	33 Δt

(*: Gaged Catchments)

NOTE: Capacity of Interceptor between Regulators Nos. 1 and 6 is 1170 cfs (33000 lit./sec.) and between Regulators Nos. 6 and 10 is 1380 cfs (39000 lit./sec.).

A constant flow velocity of 5-ft/sec (1.5-m/s) in the interceptor was assumed as a computational expedient. That is, no detailed flow routing in the interceptor was attempted. For the initial study, a Δt of 4-minutes was used, and the multiples of this Δt shown in the last column of Table 4 are the rounded values used in the initial analyses. (In the more extensive seasonal analysis performed later, next subsection, Δt was also 4-minutes).

Results of Initial Study -

Exploratory computer runs provided substantial insight to all involved, despite the fact that at that time the runoff model had not been calibrated and synthesized hydrographs were used instead, only a single reference raingage was used and considerable time was devoted to refinement and comparison of linear programming and dynamic programming optimization routines as part of the first computer program developed. Major findings were -

- No advantage can accrue to integrated control over local control unless runoff can be predicted adequately in advance, as explained early in this Section.
- Because the objective of local control is to divert as much flow as possible from the collector through the regulator into the interceptor, another variable must be added for integrated control to have any advantage over local control. Thus, even with prediction, overflows must be skewed in time and/or space to obtain any advantage for integrated control. This was argued earlier in this Section. That is, a spatial and/or temporal weighting function must be employed.
- From the preceding, for an event with an overflow, even though overflows are precluded over designated reaches or at designated outfalls, or the early portion of overflows is suppressed, the total volume of overflows for the event will be unchanged. That is, the volume held back at a designated place or for a designated period has to be discharged as an overflow sooner or later some place. To confirm this deduction, in test runs synthesized hydrographs were applied simultaneously at all ten collectors for local control without rainfall prediction and for integrated control with an 80-minute prediction. Whether or not certain outfalls were favored with lesser total overflow volumes or lesser overflow volumes early in the event, the total volume of overflows rejected by the interceptor for an event remained unchanged. For example, when no overflow whatever was prescribed for a given outfall, the volume precluded at this outfall was merely added to other outfall overflow volumes, with the total volume of overflows for the event remaining unchanged.

Still using a synthesized collector hydrograph (same basic hydrograph shape for each of the ten collectors, as before), the effect was explored of a storm moving from west to east, i.e., in the direction of interceptor flow. For this, the onset of collector runoff was delayed 20 minutes at Regulators Nos. 2, 3, 4 and 6 and 40 minutes at Regulators Nos. 5, 7, 8, 9 and 10. Due to the expected accumulation effect, the volume of overflow was 34% higher than for the comparable case where the onset of collector runoff was simultaneous immediately upstream from all regulators.

This situation was discussed in a general way in connection with the presentation of Table 2. For a storm moving against the direction of interceptor flow, discussed in a general way in connection with the presentation of Table 3, it is expected that the total event overflow volume would be less than for the non-moving case, although this was not tested.

In another exploratory test, an attempt was made to characterize the "first flush" effect cited so frequently in the literature. To that end, the following weighting was assigned: for an overflow occurring in the first 24 minutes of an event, $w = 5$ was used for all associated $(w_i O_i)_t$; for the period between 24 minutes and 60 minutes of an event $w = 3$ was used for all associated $(w_i O_i)_t$; and for the period beyond 60 minutes of an event $w = 1$ was used for all associated $(w_i O_i)_t$. For the May through September, 1978, period there were twelve rainfall events that ostensibly would have produced overflows. For these twelve events, with the preceding weighting assignments, it was found that integrated control would cause an overall weighted volume reduction of 10% over local control in the early period of the events. However, as before, the total volume of overflows for an event was unaffected by the time weighting. Unfortunately, an early volumetric reduction in overflows has only a very indirect relationship with impacts on receiving waters, which for the North Interceptor is the Riviere des Prairies. Because a less subjective objective function was wanted, it was at this juncture that all investigation shifted to a time-variant suspended solids approach.

Summer Season Analysis

Scope of Summer Season Analysis -

Rainfall data weighed by the Thiessen polygon method was from ten recording raingages, eight of which are within the combined sewer area. A 5-minute interval of rainfall was input to the hydrologic model. All storms in the May through September, 1978, period were used.

Rainfall was transformed into runoff in collectors upstream of regulators via the C.U.M. model,(7) which is based essentially on an elementary triangular hydrograph associated with a rainfall excess of one-minute duration. The time step for hydrograph calculation was 1-minute with values of runoff averaged every 4-minutes to be compatible with the optimization time step used. The C.U.M. model was calibrated for overall fit against field data for three drainage areas that comprise two-thirds of the total combined sewer area, the catchments tributory to Regulators Nos. 1, 2 and 5, Table 4. First, the model was calibrated for ten events for the tributary area of Regulator No. 5; second, the model was adapted to the other two catchments; and third, about thirty events were processed through each of these two catchments. The results from the latter were good. Actual and computed hydrograph shapes were in excellent agreement and peak flows were almost all within 10%. The model having been considered verified, it was then adapted to the seven other, smaller, regulator tributary areas.

In an attempt to account for the non-proportional variations between runoff and water quality parameters, the most basic parameter used in current models, suspended solids, was adopted for inclusion in the calculations. The time-decay relation adopted is common to just about all models that handle water quality, having appeared first in the U.S. EPA Storm Water Management Model, and later in its Canadian variant.(8) The suspended solids relations used by the C.U.M. are the same as for both the U.S. and the Canadian variant. Water quality samples had been taken at a ten-minute interval at the gaging stations of the three catchments noted above and identified in Table 4. The C.U.M. model was calibrated for suspended solids using sample data for three events on each of the three catchments. Then the calibrated version was tested against nine other events on each of the three catchments, with the result that an overall agreement within 20% was obtained between calculated and sampled suspended solids, and the calibration was then considered validated.

There are three central sources of error in any calculation of the conversion of rainfall into combined sewer overflows: errors in interceptor hydraulics estimation; errors in transformation of rainfall and pollutant accumulations into runoff and its pollutant burdens; and errors in the measurement and prediction of rainfall. The C.U.M. and E.P. have scheduled for completion by 1982 an investigation into errors introduced through use of a constant interceptor velocity (a form of time-lag routing) by checking selected runs with a detailed routing procedure, but difficulties are anticipated because of a need for compatibility between computer programs for the hydraulic relations and the optimization scheme, which must be handled simultaneously. Errors in the transformation of rainfall and pollutant accumulations into runoff and its pollutant burdens have been reduced about as far as they can be, and the amount of field data that was available for calibration and verification was unusually generous. Lastly, perfect prediction has been assumed; that is, measured rainfall as indicated by the raingage network was assumed to be known adequately in advance of its actual occurrence in the network. Planned are tests to explore the errors that would be introduced by using measured and predicted rainfall as could be obtained from the McGill University digital recording weather radar (see Section 5). However, the errors of practical interest are the overall errors embracing rainfall prediction through receiving water impact, and it will be some time before this complexity can be handled with confidence. In the meanwhile, probing tests such as those described here are necessary and desirable preambles.

Results of Summer Season Analysis -

Using the suspended solids time-decay relationship mentioned above, computation was focused on the minimization of total suspended solids load in overflows per event and for certain favored outfalls for the five-month period from May through September, 1978. While there were 42 storm events for the period, only 12 would have been associated with overflows. These were the same events for which the C.U.M. model had been calibrated and verified for simulation of suspended solids in collectors just above regulators. The prediction time used for the 12 events was 80 minutes.

Results from the runs for minimization of total suspended solids load per event are listed in Table 5. With no attempt to favor any one or more regulators over any other or to warp the timing of loadings, the average

TABLE 5

RESULTS FOR MINIMIZATION OF TOTAL SUSPENDED SOLIDS LOAD IN OVERFLOWS PER EVENT

STORM EVENT, 1978	TOTAL SUSPENDED SOLIDS LOAD ENTERING RIVER		
	FOR LOCAL CONTROL, Kg	FOR INTEGRATED CONTROL, Kg	PER CENT REDUCTION IN TOTAL LOAD
5/9	13300	11900	10
5/18	22700	19800	13
5/31	119000	113000	5
6/19	42500	41700	2
6/27	39700	37700	5
7/8	78400	74700	5
7/27	19900	19100	4
8/3	41400	39600	4
8/8	26500	26000	2
8/29(1)	41300	39800	4
8/29(2)	50500	49500	2
9/28	13700	12800	7
MEAN			5

reduction in load for the 12 events is about 5% for integrated control over local control. However, the total volume of overflows for integrated control was the same as for local control, as usual.

In another set of runs, three overflows were favored as follows: at Regulator No. 1, w = 3; at Regulator No. 3, w = 5; at Regulator No. 5, w = 3; and at the other seven regulators, w = 1. These w-values were applied as multipliers to the mass of suspended solids for the associated regulators. The results are listed in Table 6. There was no reduction in outfall overflow load at Regulator No. 1 because, in local control, overflows experienced at Regulator No. 1 are unavoidable due to its limited diversion capacity (Table 4). However, overflow loads were reduced almost entirely at the outfall of Regulator No. 3 and 80% on the average at the outfall of Regulator No. 5. The right three columns of Table 6 are similar to the entries in Table 5; and the total event load for local control is identical with that in Table 5. However, instead of the overall average reduction in load of 5% for integrated over local control with unweighted overflows for the Table 5 entries, the favoring of three overflows in Table 6 results in an overall average increase in load of 7% for integrated over local control for the twelve events. (As usual, the volume of overflows was unchanged). Thus, the successful defense of two outfalls exacts a cost of larger total loads per event entering the river.

In the last set of runs completed by June, 1980, the fixed interceptor flow velocity was raised from the 5-ft./sec. (1.5-m/s) for all previous runs to 10-ft./sec. (3-m/s). Results compared as follows:

- instead of an average load reduction of 5% for unweighted integrated versus local control for 1.5-m/s (Table 5), for 3-m/s the reduction was 7%;
- instead of an average load increase of 7% for weighted integrated versus local control for 1.5-m/s (Table 6), for 3-m/s the increase was 4%; and
- the reductions for the three favored regulators at 1.5-m/s (Table 6) were only very slightly raised for 3-m/s.

Thus, the results do not appear to be strongly influenced by the interceptor transport velocity. However, until these findings can be checked using dynamic interceptor flow conditions, it would perhaps be reckless to accept these preliminary findings without some reservation. Investigation in Montreal will continue, as already noted.

Lastly, it must be agreed that the North Interceptor is a rather unique case. Results obtained thus far for integrated over local regulator control may be unique to that case. There will probably be more attractive possibilities elsewhere, as well as situations where no real improvement can be expected. Regardless, the findings through June, 1980, indicate a good potential for protecting designated river reaches, provided that the essentially unchanged total loading to the receiving waters does not entirely offset that advantage.

TABLE 6

RESULTS FOR PROTECTION OF THREE SPECIFIED OUTFALLS IN TERMS OF TOTAL SUSPENDED SOLIDS PER EVENT

STORM EVENT, 1978	SUSPENDED SOLIDS LOAD ENTERING RIVER					
	PER CENT REDUCTION			TOTAL LOAD, ALL TEN OUTFALLS		
	OUTFALL NUMBER 1 (w = 3)	OUTFALL NUMBER 3 (w = 5)	OUTFALL NUMBER 5 (w = 3)	FOR LOCAL CONTROL, Kg	FOR INTEGRATED CONTROL, Kg	PER CENT INCREASE IN TOTAL LOAD
5/9	0	100	100	13300	15400	16
5/18	0	100	100	22700	24500	8
5/31	-1	100	92	119000	125000	5
6/19	0	100	62	42500	44400	4
6/27	-2	100	95	39700	42100	6
7/8	1	100	77	78400	84700	8
7/27	0	100	53	19900	21800	10
8/3	-1	100	100	41400	43800	6
8/8	0	100	100	26500	27200	3
8/29(1)	0	100	59	41300	42500	3
8/29(2)	0	93	27	50500	52200	3
9/28	0	100	100	13700	15800	15
MEAN						7

Concluding Remarks -

Minimization of objective functions was pursued for some time during the study using both linear programming and dynamic programming. No difference in the results and little differeince in computer running time were found. Because there was no penalty for using dynamic programming, it was employed alone in making the runs with 1978 raingage network data.

It so happens that the C.U.M. is committed to at least remote monitoring of all regulators, including those in the North Interceptor. The monitoring center is also going to be the central data processing center for the treatment plant and pumping station at the eastern end of the Island of Montreal. Further, supervisory control is wanted by the C.U.M. over its regulators. Local control, by definition, does not admit supervisory control except as an over-ride. Integrated control of regulators would make possible the imposition of supervisory control. In the case of the C.U.M., adoption of supervisory control and concomitant integrated regulator control would be a small change in commitment, and integrated control appears to be cost-effective to the C.U.M. so far.

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SECTION 4

IN-LINE STORAGE

BACKGROUND

Use of in-line storage has been viewed as a particularly attractive means for reducing combined sewer overflows, wherein the "unused" volume in interceptors and trunk sewers is exploited for temporary storage.(1) In-line storage can be induced by manipulating existing and/or added flow control devices. While in-line storage can be induced by regulator modifications and flow restriction devices, these are static and not susceptible to real-time manipulation and hence are not considered here.

Inflatable dams added beyond the point of interceptor diversion in outfall sewers have been the means for inducing in-line storage in Minneapolis-St. Paul,(2) whereas Detroit has been able to take advantage mostly of already installed control facilities.(3) The Minneapolis-St. Paul and Detroit cases might best be described as having achieved a quasi-supervisory control capability. Because Seattle has gone the furthest towards full automation with in-line storage,(4) discussion hereinafter will center on that case. Details on the intended mode of operation of the automated portion of the Seattle system have been presented in a widely available paper.(5)

SEATTLE(4)

Monthly average rainfall in Seattle is lowest from May through September, normally amounting to less than two inches per month. The vast majority of combined sewer systems in the U.S. are located in the Midwest and Northeast where May through September are normally the wettest months, with monthly average rainfalls that are commonly two inches per month or more.

Over the more than three-year Seattle automation demonstration period, total storm depths did not exceed 0.2-in. (5-mm) for three-fourths of the localized summer storms recorded. Summer total storm depths in excess of 0.2-in. (5-mm) are more common in the Midwest and Northeast. This difference is reflected in comparative intensity-duration-frequency values. For example, for a two-year average return period and durations of 5-min. through 60 min., historical rainfall intensities (or depths) for Chicago are four times those for Seattle, and similar ratios obtain for other combined sewer system cities throughout the Midwest and Northeast.

In 1973, at the end of the Seattle automation demonstration period, it was concluded that overflow reduction was most effective in the affected 13,000-acre (5,300-ha) portion of the combined sewer system for winter storms. System effectiveness during summer months was ambiguous and inconclusive. However, in a March, 1980, interview, Messrs. Theodore Mallory and Curtis Leiser indicated that effectiveness in summers since 1973 was not much different from that for winters, as a result of much more operating experience. They had originally expected this because of a strong similarity in storms from season to season. In describing the subject Computer Augmented Treatment and Disposal system (CATAD) and control facilities in a 1979 report, consulting engineers credited them with successfully reducing annual overflows by up to 30%.(6)

An important feature of CATAD was the construction of 18 regulator stations, intertied to a centralized computer control system. Most of these regulators are on the Duwamish River estuary. More important, most of the in-line storage is in the Duwamish portion of the system, where collector or trunk sewers are quite long and on uniform slopes, with an unusual in-line storage potential. Before CATAD, tide gates at the outlets of these long collectors prevented river water from entering them. Accumulated combined sewage drained from these collectors as the tidal stage receded, and thus in-line storage had earlier been induced in the collectors, but to no particular advantage. With the replacement of the tide gates with remotely operable sluice gates at the outlets, and the installation of new remotely operable regulators near the outlets, it became possible to use the induced in-line storage to maximize flows in the interceptor sewers by diverting as much flow as possible through the regulators.

Aggregate maximum, safe, in-line storage available in the Seattle collection system was 17.8-million gallons (67,400-m^3) or an average of 0.05-in. (1.3-mm) for the affected 13,000-acre (5,300-ha) area. About three-tenths of the total storm depths over a year do not exceed this amount and, considering that runoff would be a fraction of rainfall, one would expect that the in-system capacity ideally would be capable of containing quite a few more total storm depths. While design capacities of interceptors are not given in the report, actual maximum local capacities range from 2.7 to 7.3 times dry-weather flow. However, there are critical portions of the system that can accommodate as little as 2.4 times the dry-weather flow, and overall generosity of interceptor capacity is therefore difficult to assess.

MONTREAL

Listed in Table 7 are summaries of the incidence of storms for each of the three years of the Seattle demonstration period.(4) Also shown, for comparison, is the incidence of storms for Montreal for three years. The Montreal record used is for hourly rainfall at Dorval Airport. (There were missing data for 1971, and 1973 is included as a nominal replacement. Hourly data were provided by Dr. Van-Thanh-Van Nguyen, Ecole Polytechnique, University of Montreal).

As used here, a storm was defined for the Montreal data as a series of hourly rainfalls with no interruptions exceeding two hours. That is, a period of three hours or longer without rainfall was chosen as the inter-event interval. While the definition of a storm used for the CATAD system is more complex, the criterion adopted for the Montreal data is about as close to it as one can come. Another consideration would be relative storm duration or mean storm intensity, but data for Seattle are not readily available for comparison. All Montreal storm incidences were incorporated in

Table 7, including, for example, 28 of the 142 for 1973 for the full year and 12 of the 40 for June through August, 1973, with a depth of only 0.01-in. (0.25-mm), the minimum reported. This is the minimum depth used for Seattle per Mr. Leiser at the March, 1980, interview.

TABLE 7. COMPARISON OF INCIDENCE OF STORMS

City	Year	Full Year		June through August	
		Number of Storms	Total Depth, in.	Number of Storms	Total Depth, in.
Seattle(4)	1970	142	37.21	11	1.54
	1971	171	37.16	22	3.64
	1972	144	40.38	16	2.38
Montreal	1971	113	19.00	36	8.10
	1972	126	33.02	50	16.55
	1973	142	32.74	40	10.11

Regardless of the immediately preceding caveats, and even though there is no intention of suggesting that any of the entries in Table 7 are "typical," it is abundantly clear that the number of storms and their cumulative depth for June through August are at least twice as great in Montreal as in Seattle. Values taken from plots and tables in the Seattle report(4) for a full year (4/1/72 - 4/1/73) and for May through September over the demonstration period are graphed in a tentative context in Figure 7. Also graphed in Figure 7 are the distributions of total storm depths for 1973 for Montreal. Again, while these indications are not necessarily typical, it appears that control demands for Montreal are more rigorous than for Seattle.

In-line storage was considered for the North Interceptor of the Montreal Urban Community in 1974.(7) Calculations were based on the use of fabridams of the type employed in Minneapolis-St. Paul(2) located just downstream from regulator diversion points, and gates at the outfall exits that would trap flows that would later be pumped to the interceptor. Summer river stages can submerge the outfalls of the larger basins. Further, exploitation of in-line storage between fabridams and outfall gates is not possible for one-sixth of the total combined sewer drainage area of the North Interceptor. In consequence, the computed in-line storage potential was only 0.027-inches (0.7-mm), about half the volume that can be exploited in Seattle. This is unfortunate because the North Interceptor drainage area of 30,000-acres (12,000-ha) is more than twice as large as the drainage area under remote control in Seattle, and would otherwise provide a better economy of scale. However, with more numerous and larger summer rainstorms in Montreal than in Seattle, much more in-line trunk storage than in Seattle would be required in Montreal to achieve an equivalent reduction in overflow incidence and/or volume. Parenthetically, the potential in-line storage in collectors of the North Interceptor of Montreal was about evenly divided between that above fabridams and that downstream between outlet gates and the fabridams. If the Montreal storage potential was restricted to that which might be obtained with outlet gates, as in Seattle, the available storage would be

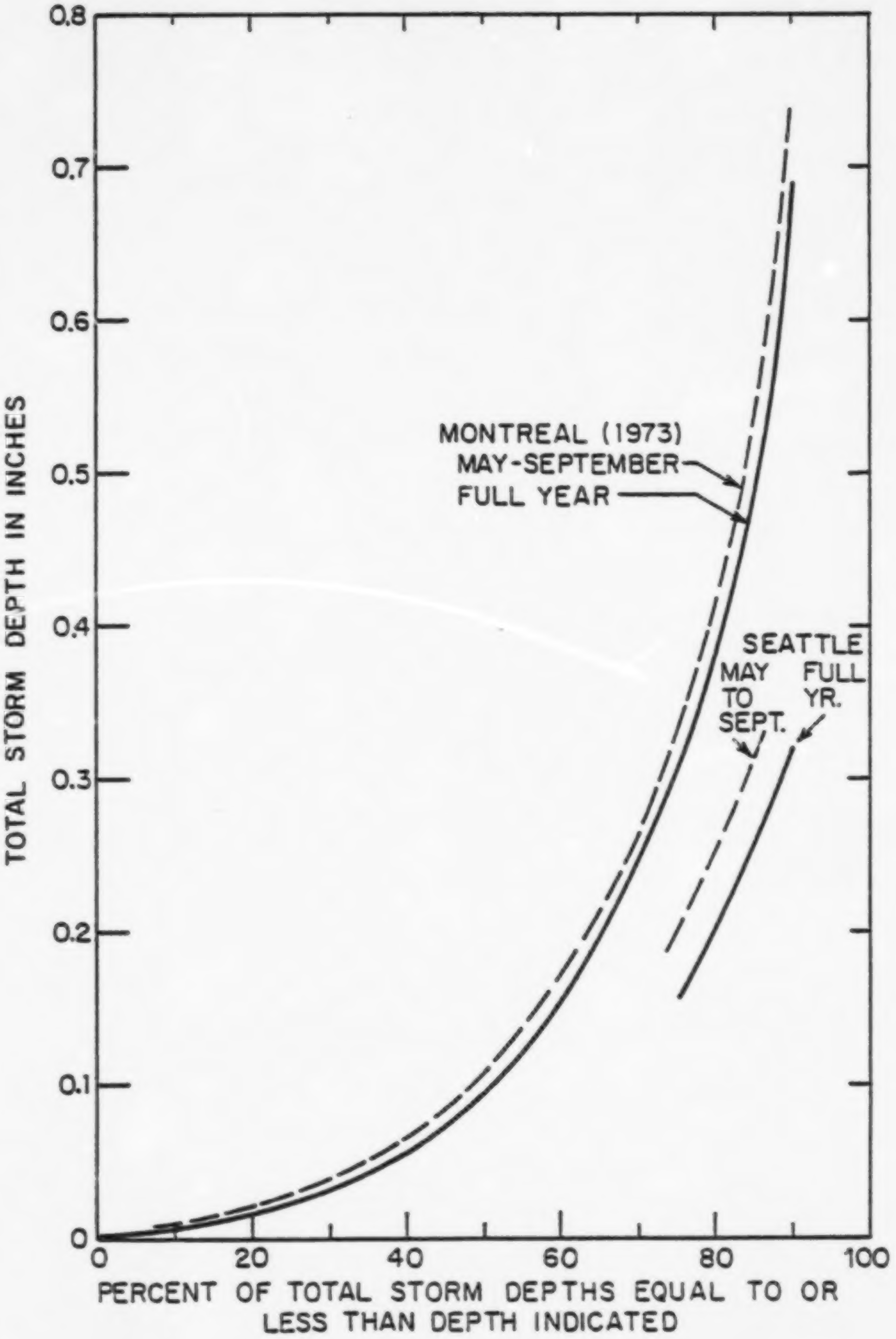

FIGURE 7- COMPARISON OF TOTAL STORM DEPTHS

only about one-fourth as large as in Seattle.

The above conclusions must be tempered by the criteria used in making the storage calculations. It was assumed that the maximum depth of quiescent storage that a fabridam would hold would be three-fourths of the height of the outfall sewer just downstream from the regulator, and that stormwater that could be trapped behind a flap gate at the exit of the outfall sewer could be dewatered by pumping it to the interceptor between storms. That is: at the onset of a storm the outfall would be essentially free of stormwater and the fabridam would have been deflated; all flow not diverted to the interceptor would at first be collected behind the flap gate; and when the water level behind the flap gate reached that of the river the fabridam would be fully inflated to store as much more water as possible. At the cessation of storm inflow, the water remaining behind the fabridam would completely drain to the interceptor, when capacity was available the water behind the flap gate would be pumped to the interceptor, and with the fabridam deflated the cycle of operation would be completed and the outfall would be ready for the next storm. While the use of remotely operated sluice gates, as in Seattle, would provide more effective manipulation of flows and storage than would flap gates, only a self-actuating device was considered for the Montreal calculations and the Milwaukee calculations which follow. In any event, a true direct comparison with Seattle is not possible because the Seattle configuration did not require the use of fabridams, the outfalls being on a uniform slope, whereas the Montreal outfalls mostly break into a steeper slope between the regulator locations and the outfall exits.

Mr. Nguyen Van of the Montreal Urban Community brought the 1974 North Interceptor study to our attention. He also provided important help in technical interpretation of the study report.(7)

MILWAUKEE

Included in a 1969 survey of sewered drainage catchments in sample major cities(8) was all separate storm sewer and combined sewer areas in Milwaukee. Close to one-third of the total drained area was served by combined systems. The total area of all 465 catchments was 43,000-acres (17,000-ha), and the catchments ranged in size between 2- and 1,820-acres (1- and 717-ha). Taking all 465 catchments into account, it was found that three-fourths of them were less than 70-acres (28-ha) in size and that half of them were less than 25 acres (10-ha) in size. A predominance of smaller catchments was also noted for the other three major cities surveyed. While the combined sewer catchments were not segregated in the survey, the available evidence seems to indicate that the median catchment area size for large U.S. cities is less than 200-acres (80-ha), and may be less than 100-acres (40-ha), for either combined sewer or separate storm sewer drainage areas.

Catchment size and outfall sewer size for six typical Milwaukee combined sewer drainage areas were reported in the 1969 survey:(8)

Catchment No.	Drainage Area	Outlet Size
1	465 acres	10' diameter
2	80 acres	2 @ 4' diameter
3	25 acres	42" diameter
4	75 acres	9.25' x 4.5'
5	40 acres	30" diameter
6	175 acres	6' diameter
	860 acres	

On request, potential in-line storage for these six catchments was kindly computed and provided by the Milwaukee Department of Public Works at the initiative and under the direction of Mr. Edwin J. Laszewski, City Engineer. Criteria used in the 1974 Montreal calculations were adopted, including the assumption that the maximum depth of quiescent storage that a fabridam would hold would be three-fourths of the height of the outfall sewer just downstream from the regulator, and that water that could be trapped behind a flap gate at the exit of the outfall sewer could be dewatered by pumping it to the interceptor between storms.

For the total 860-acres (340-ha), the calculated maximum storage was 210,000-ft.^{3} (6,000-m^3) or 0.067-in. (1.7-mm). However, 79% of this collective potential storage is for Catchment No. 1, and 60% of this potential collective storage is for storage between the flap gate and the fabridam of Catchment No. 1. While Catchment Nos. 2 through 6 drain into the Milwaukee River, Catchment No. 1 drains into Lake Michigan and there are not many of such cases in the Milwaukee system. That more than half of the potential storage in the six catchments resides in only one of the six catchments, and for potential storage only in the reach between the flap gate and the fabridam, strongly suggests important limitations in the exploitation of storage on a system-wide basis in Milwaukee.

As pointed out in the next subsection, it is not practicable to install fabridams in smaller than walk-through size combined sewers, and taking the minimum walk-through height as 54-in. (1,370-mm) as proposed there, only Catchment Nos. 1, 4 and 6 qualify. For these three catchments, there are 0.024-in. (0.61-mm) of potential storage above fabridams and 0.049-in. (1.25-mm) of potential storage between fabridams and flap gates, nearly all in Catchment No. 1. If this more practical storage for the three walk-through outfalls is divided over the full 860-acres (340-ha) of all six catchments, the total potential storage reduces to 0.061-in. (1.54-mm).

While the Lake Michigan outfall (Catchment No. 1) has an attractive potential for exploitation of in-line storage, the case for river outfalls, which are much more numerous, appears to be particularly weak. An unreported study of potential storage, performed for the Milwaukee Metropolitan Sewerage District some years ago, indicated a small overall combined sewer system potential storage capacity, which tends to confirm the reservations reached from the values of storage computed for the small sample of only six catchments reported here. Lastly, it must be noted that a flap gate would not be installed on the outfall exit of Catchment No. 4 because the outfall invert elevation at the Milwaukee River is higher than the present river level.

SEWER SIZE DISTRIBUTIONS

Fabridams were installed in Minneapolis-St. Paul(2) and outlet sluice gates were installed in Seattle(4) only in the larger collector sewers. A walk-through size is needed for construction, operation and maintenance of these types of controls.

Milwaukee was one of five major cities surveyed for sizes of combined sewers in 1967.(9) Of the total length of combined sewers in these cities, it was found that on the average about 15% were 54-in. (137-mm) or larger in the vertical dimension. A 54-in. (137-mm) vertical dimension was regarded as the minimum walk-through height. If exploitation of in-line storage is restricted to walk-through size combined sewers, numerous small catchments will be overlooked that may comprise a significant part of a total system. According to the 1967 survey,(9) an average of 72% of the total length for the large cities sampled was equal to or smaller than 24-in. (61-mm) in diameter, and many outfalls must fall into this category. From a national perspective it is important to realize that many combined sewer systems exist in the smaller cities, and for cities with a population of 100,000 persons or less the proportionate length of walk-through size was found to be half that for the large cities.(9) The finding of predominantly small outfall sewers is consistent with the finding of predominantly small catchments. In sum, it appears that in-line storage exploitation is restricted to only a part of any given combined sewer system because of a preponderance of small catchments and associated small outfall sewers. However, several static in-line storage techniques might be found to be suitable for the smaller sewers.

ANOTHER CLIMATIC EXAMPLE

Returning to the question of rainfall differences, the Gulf climate offers still another comparison. Defining a storm event as a period of uninterrupted rainfall, a three-year record for Orlando, Florida, centrally located in that State, has the following attributes:(10)

Per Cent of Total Storm Depths Equal to or Less than Depth Indicated	Total Storm Depth, Inches
90%	1.0
80%	0.5
70%	0.3
60%	0.15
50%	0.1

The above attributes are quite similar to those in Figure 7 for Montreal, and although the definition of storm event is an issue, it appears nevertheless again that the departures from Seattle storm characteristics elsewhere can be substantial. Further, the greatest rainfall in Orlando occurs during the summer, as opposed to the winter in Seattle.

CONCLUSIONS

Use of in-line storage in automated systems was regarded in 1975 as being particularly attractive for large, flat and deep trunk and outfall sewers.(11) "In-line storage including real-time control of the collection system is a viable alternative if the existing collector system has a large interceptor storage capacity."(12) It is abundantly clear that the potential for in-line storage will vary from region to region, from system to system within a given region, and even from sector to sector within a given system. The feasibility of using in-line storage should be evaluated on a case-by-case basis. In-line storage can be a clearly limited but valuable resource, and should not be overlooked as a potential to be investigated in overall combined sewer overflow facility planning.

Of special interest here is the decision step adopted in Seattle in connection with in-line storage. "It is only when allowable interceptor flow has been reached at one or more points in the interceptor that storing is commenced in the trunk sewers."(4) This means that in-line storage can be regarded not only as a physical add-on to a conventional regulator-interceptor system, but that the control logic can be added in an incremental way to that for local or integrated control of a regulator-interceptor system.

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SECTION 5

DIGITAL RECORDING OF RAINFALL BY RADAR

PREFACE

The intended audience of this Section is primarily the civil engineer interested in automatic control of either combined sewer systems or separate storm sewer systems or in flood warning systems for urban streams. It is widely accepted that attainment of a reactive mode of real-time control or warning would require a telemetered raingage network spanning the affected jurisdiction. Not so well recognized is that to advance to a predictive mode would require extension of such a network as far away as 100 miles (160 km), a substantial impediment, in order to anticipate rainfall on individual catchments two or three hours in advance. An attractive potential alternative to scores of raingages deployed far and wide as a means for predicting rainfall is a recently emerged extension to digital recording radar capability. Summarized in this Section is the state of the art in radar rainfall measurement and prediction from the viewpoint of potential applications in urban water resources operations.

For about the past three years, civil engineers have posed the question: "what can you meteorologists give us that we can use for automatic control of urban water resources systems involved with pollution and flood control?" Very logically, the meteorologists have replied: "what do you need?" An objective of the project reported here was to develop more definitive versions of these questions and to see how far the answers could be firmed. The heart of the matter is accuracy. While the accuracy of rainfall measurement and prediction is an obvious factor that will influence the degree to which automatic control can be reached, the ultimate concern of the civil engineer is the accuracy to which anticipations can be made of combined sewer overflows, discharges from separate storm sewers and stages of urban streams. That is, the answer to the question of accuracy is complex, being the net effect of imprecisions in rainfall measurement and prediction, errors in assessment of abstractions from rainfall to arrive at direct runoff, fidelity of hydrologic routing over the land and hydraulic routing in channels, plus any doubts about the efficiencies of flow control or diversion structures. This is compounded in the case of water pollution control with uncertainties about the impacts of urban runoff pollution on receiving water bodies; and it is these impacts which are the sole objective function in that case.

Until adequate error analyses of the full sequence of rainfall prediction through receiving water impact are made, it will not be possible to determine the degree to which attainable precisions in radar rainfall measurement and prediction limit or constrain anticipation of receiving water quality and urban stream stages. It is conceivable that uncertainties with radar are no worse than those in the hydrologic, hydraulic and water quality transformations employed. Regardless, it is imperative that the civil engineer know the precision level of radar indications so this can be factored into interpretations of uncertainty over rainfall-runoff-water quality computations.

The writer is greatly indebted to several meteorologists, four in particular, who provided information and advice in advance of this endeavor. In order of the conferences held at their offices, they are: Dr. Michael D. Hudlow, National Weather Service, NOAA; Dr. Pauline M. Austin, Massachusetts Institute of Technology; Dr. Geoffrey L. Austin, McGill University, Montreal; and Mr. Stanley A. Changnon, Jr., Illinois State Water Survey. This Section has benefited materially from their input; however, the writer is solely responsible for its content. Much of the coverage herein of weather radar performance is based upon class notes by Drs. Pauline Austin and Spiros Geotis(1) and a text recommended by Dr. Austin.(2)

GENERAL DESCRIPTION

"Radar," a contraction of "radio detection and ranging," is a means for detecting the position, motion and nature of a remote object in the atmosphere. Radar was developed in several countries, mostly in the late 1930's, received substantive improvement during World War II and has been improved much more since. Although radar was initially designed to detect aircraft, over thirty years ago it was found that microwave radar (wavelength of 1 cm to 20 cm) would indicate the presence of precipitation within its scanning range. From a hydrological viewpoint, the maximum useful range of a weather radar is about 200 km (125 miles).

Being electromagnetic, radio waves travel along straight lines in a vacuum at the speed of light. The atmosphere bends these beams slightly towards the earth. In order to focus upon an object in the sky, transmitted electromagnetic energy is reduced to a narrow beam by means of a directional antenna. In contrast, as the name implies, radio broadcasting signals are transmitted by a mostly non-directional antenna. Radar power is usually transmitted as pulses of radio waves of short duration, such as a microsecond, and the frequency at which pulses are emitted is on the order of one thousand per second.

Some part of the energy of the pulses is reflected back to the radar by objects that intercept them and these reflections are picked up by a receiver, processed electronically and, in the usual case, are converted into visible form as small dots of light on the face of a fluorescent screen of a cathode-ray tube. The range of an object is determined by measuring the time of travel for the signal to reach an object and return, and the direction of an object is indicated by the position of the antenna at the instant of signal transmission. The antenna of an operational radar is normally rotated continuously at a constant speed. Most weather radars can be elevated from slightly below horizontal to vertical, use a single antenna for both transmission and reception and use symmetrical beams with widths of one to three degrees.

Signals reflected back to a radar from an object are termed "backscattered energy," and the most extensively used indicator of backscattered energy on weather radars is termed the "plan-position-indicator" (PPI). A PPI displays in polar coordinates a plan view of the received signals. "Range markers" are concentric circles at a uniform radial distance apart, such as 25 miles, that also appear on the scope. The range and bearing of a discrete target therefore can be read from a PPI display. Furthermore, the brightness of a backscattered point represented on the display depends on the strength of the returned signals, or the "echo intensity," and generally the greater the mass of precipitation at a point in space, the greater the corresponding display point brightness (echo intensity) on the scope.

Another type of radar display, used with radar antennas that scan vertically, is the "range-height indicator" (RHI). An RHI presents the position of individual reflective points in space on a coordinate system with range as abscissa and height as ordinate. RHI displays are used in cloud physics research.

By now, a reader concerned mostly with water resource applications will have discerned that neither the PPI nor the RHI, or even their combination, may be of exclusive interest. The "plan" of a PPI is for a given vertical angle of antenna sweep inclination; a horizontal antenna orientation permits the sensing of only one plane, as high as the antenna at its site but enlarging with distance from the site due to the earth's curvature; and at all other inclinations the "plan" is actually that for a shallow cone. What would appear to be more flexible would be a set of plans of reflective points on curved spatial surfaces, each at different but constant altitudes. Just such a technique was developed by the Stormy Weather Group at McGill University in Montreal, called "constant-altitude plan-position indicator" (CAPPI), as reported in 1957. More about this later.

Determination of the location of a score or more targets by use of radar, such as in air traffic control, is indeed an impressive accomplishment. But in weather radar we are dealing with thousands of targets even though echoes are for averages of small volumes of space occupied by some precipitation. Consider that for over any small displacement of antenna sweep there may be dozens or even hundreds of echoes received and displayed/processed. The marvel of this capability has its source in a complex electronic switching system that segregates and controls outgoing pulses of energy and incoming reflected energy from various ranges along any given line on which the antenna is pointed.

Meteorologists commonly divide the microwave spectrum into bands and describe radar sets in terms of wavelength, λ, rather than in terms of the frequency, f:(2)

Frequency, f (MHz)	Wavelength, λ (Cm)	Band
30,000	1	K
10,000	3	X
6,000	5	C
3,000	10	S
1,500	20	L

The wavelength of most weather radars is fixed, and the smaller the size of the targets the shorter the wavelength required to detect the targets, with other radar hardware characteristics remaining constant. "For example, an S-band radar can generally detect rain but not cloud droplets, while a K-band radar will detect many clouds even though they are not yielding precipitation."(2) As with most highly refined instruments, there are trade-offs in the selection of a given radar. We will be focusing mostly on S-band, or 10 cm radars.

PRECIPITATION DETECTION(2)

Theoretical relationships have been developed between radar set performance parameters and backscattering properties of spherical particles. Precipitation detection uses empirical modifications of these basic functions. Volumes in space of specified size are used as collective targets rather than the individual particles of precipitation within each such volume. Echoes from such volumes fluctuate due to the movement with respect to one another of the randomly distributed particles therein. Wave phases of backscattered signals from individual particles change as the particles move over time, with the result that the vector summation of signal contributions changes from one pulse to the next. "The backscattered signal voltage from a volume of randomly distributed scatterers is the sum of the signals scattered by each of the scatterers, with the phase of each signal taken into account."(2) The volume at issue is V_m, given approximately by $\pi(r\,\theta/2)(r\,\varphi/2)\,h/2$, where r is the range to V_m, θ and φ are the horizontal and vertical widths of the radar beam in radians, respectively, and h is the distance traveled by the signal pulse transmitted by the radar. Thus, the reflected power at any given time comes from all the particles in a volume encompassed by the beam aperature and half of the pulse length, a volume which grows in size with increasing range.

Letting $\overline{P}_r$ be the average power returned to the antenna from V_m:

$$\overline{P}_r = C|K|^2 Z_e/r^2 \qquad (1)$$

where C is a constant depending on the characteristics of the radar set, $|K|^2$ is the Complex Index of Refraction of the target (taken as 0.93 when the target is water), Z_e is the "effective radar reflectivity factor" and r is the range to V_m. In comparison, the theoretical average returned power for spherical particles is as in the above equation, but with Z (the "reflectivity factor") in place of Z_e. The theoretical reflectivity factor Z is commonly expressed as $\Sigma n_i D_i^6$, where n_i is the number of drops of a D_i

discrete diameter size interval, assuming that all particles in each interval have the same size. Two important points are revealed from the above: (1), the effective radar reflectivity factor, Z_e, can be calibrated empirically by comparing field raingage measurements of actual precipitation; and (2), Z_e is proportional to the sixth power of particle size and hence will vary for different types of rainfalls, and for hail, snow and combinations thereof.

For water resources applications we are interested in the rate of precipitation, but not particularly in the power returned from precipitation to the radar receiver. Described next are empirically determined relationships between Z_e and precipitation intensity.

PRECIPITATION QUANTIFICATION

Just mentioned was the uncertainty on particle size in the volume V_m. Another source of uncertainty is the attenuation of microwaves by atmospheric gases, clouds and precipitation, causing a reduction in the intensity of the electromagnetic wave along its path. Attenuation is caused by absorption of power and scattering of power away from the beam. Whereas gases, cloud droplets and small raindrops act primarily as absorbers, when large raindrops and/or snowflakes are present both absorption and scattering must be considered. However, attenuation decreases with increasing wavelength and is less significant at wavelengths in the 5-cm and 10-cm bands, the range of radars we will be describing later.

The rate at which water reaches the ground is termed R, expressed in mm/hr. Rainfall can be estimated by radar by relating Z_e and R. Considerable research has been conducted on Z_e-R relationships. It has been concluded from these collective investigations "that properly calibrated radars can make reasonably accurate measurements of rainfall intensity and of accumulated rainfall over a small catchment".(2)

Numerous studies have been made of drop-size distributions as a function of precipitation, applying statistical-type analyses to the data. Similar studies and analyses have been made of the relationship between liquid-water content, M, and precipitation rate, R, and empirical evidence indicates that Z_e is roughly proportional to M^2.

In order to convert radar signals into rainfall intensity, most investigators have employed an empirical expression in the form

$$Z = AR^b, \qquad (2)$$

such as 200 $R^{1.6}$, where Z is in millimeters to the sixth power per cubic meter and R is in millimeters per hour. To obtain estimates of rainfall from radar measurements, Z_e is normally taken as Z. Of the numerous empirical versions reported, with values of A and b covering a rather wide range, most do not yield rainfall estimates that differ greatly in their values at rainfall intensities between about 2 mm/hr. and 20 mm/hr., suggesting that the type of rainfall is more of a determinant for larger intensities. However, Z_e-R relationships have been found to vary from one locality to another and to change considerably at a given locality for different types of rain and different synoptic conditions. That a given radar should be calibrated cannot be denied but, as we shall see, the preferred type of calibration, post facto versus current time, is a matter of opinion. Regardless, final calibration of the radar-rainfall estimate against selected surface raingage estimates will be required to achieve maximum accuracy. One of the difficulties is that rainfall is measured from a volume above the ground by radar whereas rainfall at ground level is wanted by the hydrologist.

Of considerable importance in water resources applications is the fact that a number of investigators have developed schemes in which the plan-position-indicator (PPI) presentation is divided into rectangular or square grid areas and R is calculated for each such applicable area. These presentations are now fully automated in instances to be cited. Suffice it to say for the moment that ranges of R can be color-coded or indexed to a digital code in connection with a grid display. As with other areas of scientific and technical endeavors, opportunities have been taken to exploit the astounding growth in data processing capability made available mostly over the past about a dozen years. However, digitized radar data has been generated for at least that long, albeit at first in specialized studies.

Not to be overlooked as we concentrate on the use of radar for rainfall measurement is the fact that ever since its introduction to meteorology, radar has been used extensively to observe the formation and movement of thunderstorms, as in the prediction of the arrival of a thunderstorm over a particular place such as an airport. Also, radar observations have been used to confirm or augment larger-area weather observations.

PRECIPITATION ESTIMATES(1)

To reiterate, fluctuations in signals received by the radar result from changes in phase between waves scattered by individual particles moving relative to one another. The average received power in a volume V_m is equal to the sum of the powers which would be received individually from the particles in V_m. Accuracy of the measured signal power depends primarily on the number of independent samples over which the average is taken. "The number of 'sampled volumes' in the area viewed by the radar is extremely large, usually on the order of 10^5, so that averaging the signal from each one for a long time is not feasible. Some compromise must be made between accuracy and speed of data acquisition. ..... a practical limit on the number of samples contributing to the average is set by the need to scan with the antenna and by the time variability in the storm structure. In practice, an average of about thirty independent samples [within each V_m] can be readily achieved."(1)

The conversion of radar reflectivity into precipitation rate can be affected by meteorological conditions. For example, observations have often shown a progression from relatively high Z_e values (large drops) at the beginning of showers to relatively small Z_e values (small drops) in the trailing portions. Another example is the presence of hailstones, most of which are larger than the biggest raindrops, which can cause a considerable increase in reflectivity while having a relatively small effect on the rate of precipitation.

"In widespread precipitation, whether or not it contains convective cells differences between the precipitation sampled by the radar and the rain at the surface can at times be large and also vary with range. Because errors attributable to this effect differ greatly from storm to storm, limitations which they impose should be taken into account in individual storms rather than be treated statistically by having the average effect applied in every storm."(1) On the other hand, discrepancies between measurements made simultaneously at a selected point with a raingage and a radar do not necessarily imply an error in the radar measurement because the area sampled by the gage is quite small compared with that for the radar, an area of about 10^5 square meters or larger. For thunderstorms and isolated convective showers the odds are high that more accurate momentary areal intensities of rainfall will be recorded by an accurately calibrated radar than by raingages, whereas the total storm depth estimates from the two will generally be more in agreement.

There are four primary sources of uncertainty in the measurement of surface rainfall with a radar, none of which is either definitely predominant or clearly negligible: (1), methods of signal averaging; (2), radar calibration; (3), Z_e-R relations; and (4), differences between the precipitation sampled by the radar and that reaching the ground. "The first two are mainly instrumental and can be controlled and evaluated more readily than the others: nevertheless they should not be treated casually, as has often been the case. The third reflects the variability of drop size distributions in natural rain and because of this has been looked upon by some as imposing the ultimate limitation on the accuracy of radar measurements of precipitation. The fourth, however, is also dependent on the storm structure and in some cases can be extremely significant."(1)

In 1971 it was posited that, for convective storms within a range of about 150 km, an accuracy in estimating rainfall by radar of a factor of two or better could then be achieved(1) and, as a result of advances made since, the present range of accuracy is said to be much better. However, for stratiform storms, radar measurements must be interpreted with a great deal of caution, except at close ranges, because the precipitation may be modified in relatively short vertical distances.

RAINFALL PREDICTION

Development of a capability for using digital weather-radar records for short-term precipitation forecasting has been pursued for some time by the Stormy Weather Group at McGill University, Montreal, Quebec. Their first published progress report was in 1974, when they acknowledged that: "The idea of using radar records of precipitation for forming short-term weather forecasts has been inherent in radar meteorology since its inception."(3) By means of an on-line mini-computer, pattern recognition techniques were used at McGill to estimate the average motion of a digitized precipitation pattern. Successive observed storm patterns Δt apart were used to project the expected pattern at a subsequent time Δt later for a square grid of reflectivity values. The predicted displacement vector for the subsequent Δt was taken as the observed displacement vector over the prior Δt, defined by the best cross-correlation between values of measured radar reflectivity Z_e in the grids for the two prior observations. This procedure is self-correcting because a given pattern projection for an upcoming Δt is always based on two prior observed patterns over the preceding Δt.

Parenthetically, for storm tracking using digital data it is necessary to omit echoes from high ground and tall structures along the beam path. Also, when the radar beam is horizontal, there are superfluous echoes from "ground clutter" in the immediate periphery of the radar which must be omitted. In the case of the McGill radar the radius of ground clutter is about 12 km. Because of this local blind sector, radars are usually sited somewhat away from areas for which rainfall data is particularly wanted.

Late in 1978 the Stormy Weather Group reported that they had been automatically generating precipitation forecasts in the zero to three hour range as part of a real-time operation for a period of two years.(4) The 10 cm McGill radar, which has a 30 foot diameter antenna and is situated near the westernmost end of Montreal Island, is presently the only digital record radar in the world generating short-range forecasts automatically every day. Mentioned earlier herein was the "constant-altitude plan-position indicator" (CAPPI) developed at McGill in the 1950's. Their current forecasting procedure is essentially as just outlined, wherein digital CAPPI grid maps are made for a 3 km elevation plane above the ground via a mini-computer on-line with the radar, and pairs of maps of measured rainfall one-half hour apart are used to extrapolate expected grid rainfalls at half-hour intervals up to three hours in advance.

Grid sectors of maps of the CAPPI type are called "bins". The bin size for reporting the incidence of rainfall is 5 km x 7 km. Digital maps are continuously transmitted via teletype every 10 minutes to Dorval Airport on the Island of Montreal and the Quebec Region Forecast Centre of the Canadian Atmospheric Environment Service whenever significant rain areas occur or are expected. Rainfall intensity is reported according to the following code:(4)

Symbol	Lower Threshold of Rainfall Intensity, mm/hr.
1	1
2	2
3	3
4	5
5	8
6	13
7	20
8	30
9	40
A	50

(Continued)

B	75
C	100
D	150
E	200
F	300

However, estimated intensities for each grid to three significant figures can be accessed if wanted. Cumulative hourly amounts of measured rainfall are also transmitted by teletype.

As a part of standing operating procedures, predicted rainfall intensities are also transmitted via teletype, on the basis of the same 5 km x 7 km bins. Local governments in the Montreal region could access these plus predicted amounts for bins as small as 1 km x 1 km via a telephone tie-line. Also, because the duration of a three-dimensional scanning period for the McGill radar is 5 minutes, access could be had to 5 minute observations in lieu of the standard 10 minute observations. Incidentally, in a three-dimensional radar scan there are 2.3 x 10^6 data sites within the 200 mile range circle of the radar, one such 5 minute scan covering 26 elevation angles, using 148 range bins and with 600 azimuths per 10 second rotation.

The radar measurement and forecasting system in use at McGill University has been developed into a commercially available unit which digitizes, processes and transmits appropriately designed data sets for water resources use. This equipment is a stand-alone add-on to a weather radar meteorological system consisting of a digitizing interface, a mini-computer and customized software.

The Stormy Weather Group is working towards a rain tracking capability to serve the region of eastern Canada. Because of the gigantic size of the region, use of weather satellite data in some way would be essential. The reliability of satellite indications of raining areas of clouds has been tested against McGill radar indications in the Montreal area. Useful rain maps have been generated for the types of weather systems examined.(5)

Going to the other end of the scale of size, the Group has long been interested in the use of radar in urban hydrology.(6) The radar and raingage records of summer storms occurring between 1969 and 1972 over the City of Ottawa, some 136 km from the McGill radar, were used to study events which lead to the flooding of house basements in Ottawa.

ILLINOIS STATE WATER SURVEY

Since 1976 the Survey has spearheaded a series of meteorological research projects by twelve organizations, in the area over and around the southern tip of Lake Michigan, under the label of the "Chicago Area Program". There are five components of the Program: (1), urban-induced weather and climate modification; (2), study of severe storms of the Midwest; (3), study of the impacts on the atmosphere of energy production; (4), urban hydrometeorology; and (5), meteorology of Lake Michigan.(7) Of interest here is the urban hydrometeorology component,(8,9) called the Chicago Hydrometeorological Area Project (CHAP), but only the parts thereof that are concerned with radar measurement and prediction of urban rainfall. An objective of CHAP is to develop a rainfall prediction capability for urban water resources operations.

Instrumentation for the CHAP project has included a grid of 320 recording raingages distributed over an area of 4,000 mi^2 (10,000 km^2) and a 10 cm radar with a 20 ft diameter antenna located near Joliet, Illinois, southwest of Chicago. Some of the raingages were in portions of northwest Indiana and southwest Michigan bordering the Lake. Most of the raingages were spaced about 3 miles apart, with a 6 mile spacing on the fringes of the experimental area. CHAP radar operations were conducted in July-August, 1976, and April-October, 1977,(7) and were extended in 1978,(10) all with the full network. In June-August, 1979, operations were resumed, but for a reduced network of 71 raingages, for a special demonstration to be cited.

With respect to urban water resources operations, the Survey deduced that heavier rains would be the more important in the Chicago area and hence concentrated their field radar operations on the summer months. Consistent with this emphasis, the part of CHAP in which we are interested was pursued in terms of four radar tasks:

a. Historical radar data from the region were studied as part of a preliminary radar climatological assessment to appraise such things as general echo motions and their durations.(11) The assessment was useful in the design of the CHAP system, including the decision to locate the radar to the south of Chicago. Survey meteorologists emphasize that this kind of evaluation should be made in other metropolitan areas prior to the modification or installation of a radar facility for local government use.

b. Extensive radar studies were made of individual storm events. Results of these studies have appeared in several reports and papers, but two papers in particular may be of interest to the reader.(12,13) The Survey regards these types of analyses as being very informative and useful for later capability development to discern how well the radar can describe the morphology of a storm and identify centers of heavy rain.

c. Analyses were made of actual radar-raingage statistical relationships. From these were determined how well the radar can estimate rainfall under different kinds of storm conditions, the types of adjustments that must be considered for real-time radar operation, and other factors such as the separation of the detection of rain and hail from radar signals. For this task, four 1976 storms and twelve 1977 storms were used.

d. The fourth task was the development of a radar echo-rain prediction system. This task and that immediately preceding are described in more detail below.

Adjustment of radar indications with raingage measurements(9) was made for a number of storms using the Brandes(14) approach. Results were monitored using a locally-derived Z -R relationship. The full network of 320 raingages was used to evaluate the accuracy of radar adjustment methods. "Accuracy is evaluated through use of subnetworks of various density, so as to determine gage density requirements for use with the adjustment technique. Gage requirements for radar adjustment are evaluated by gradually reducing the number of gages used for this purpose from the maximum of 1 gage/25 km^2 to 50, 100, and 150 km^2/gage, which is considered the lowest density applicable in the urban real-time analysis procedure. Rain measurement error is also determined as the sampling area increases. Several subareas of various sizes within the network are used for the evaluation of measurement error with various combinations of radar and raingages. ..... The size of errors is being investigated also through stratification of the data by synoptic weather conditions and precipitation types."(9)

A tracking procedure has been developed based on lag correlation (plus another procedure) as a method for storm system tracking and prediction of urban rainfall (area mean and maximum point) for three sectors of Chicago for 30, 60, and 120 minutes in advance. In the measurement of 30-minute amounts for urban hydrologic applications, the radar is said to do better than raingages alone when the gage density approaches 1 gage/150 km^2 (1 gage/60 mi^2).(9) "The utility of radar in the prediction and monitoring of heavy storms for guiding the operation of urban hydrologic systems will be clarified better"(9) after the 1979 demonstration period data have been evaluated. Earlier data, for four storms in 1976 and twelve storms in 1977, are identified in a 1977 paper.(15)

"The basic approach to solving the real-time predicting and monitoring of heavy rainstorms in urban areas involves the use of a combined radar-raingage system in which data from telemetered raingages would be used to adjust the radar-indicated rainfall distribution."(9) The Metropolitan Sanitary District of Greater Chicago (MSD) is a special district with responsibilities for water pollution and flood control and some aspects of river navigation. In this connection, the MSD maintains 22 recording raingages from which signals are telemetered to its Waterways Control Center at its downtown Chicago headquarters. In order to show how such a telemetered network could be expanded to cover more remote locations in combination with a radar for rainfall measurement and prediction, the Survey sustained its 71 recording raingages in the metropolitan area for post-facto evaluation, used real-time data from the existing 22 MSD raingages telemetered to their radar, installed a receiver in the MSD headquarters connected by telephone line to its radar facility, and transmitted data every 30 minutes without interruption over a June-August, 1979, demonstration period. (Initial tests with a hook-up to the MSD had been made late in 1977). On August 13, 1979, the Survey conducted a one-day demonstration of its system's capabilities for representatives of 13 cities that are widely distributed across North America.

During the 1979 demonstration period, when rain occurred the Survey's system transmitted maps of radar-indicated rainfall amounts since the beginning of rain, every half hour, for many points over various sectors served by the MSD. Simultaneously, every half hour the system transmitted radar-indicated estimates of rainfall amounts that were likely to occur over various MSD sectors during the succeeding 30 minutes, 60 minutes and 120 minutes. The demonstration period, which ended on August 15, 1979, featured 24-hour supervision. However, the radar was operated only when rain was expected by the meteorologists at the radar site on the basis of meteorological information provided by their own analysis of weather data from the National Weather Service, done continuously and based on nationwide soundings of upper-air conditions. The MSD was alerted whenever an approaching storm was expected.

Also generated by the radar computer in 1979 were rainfall amounts at 2 mile by 2 mile grid points over a 128 mile by 128 mile array that could be positioned anywhere within a circle having a radius of 140 miles from the radar. For the demonstration period, the MSD received radar-indicated rainfall amounts to the nearest 0.1 inch on a 4 mile by 4 mile grid covering an area of about 2,000-square miles plus means for the three Chicago sectors.

The minimum number of telemetered raingages that would be needed for an adequate radar-raingage system for rainfall measurement and prediction in the Chicago area will be resolved by the conclusion of CHAP in 1980. However, it should be much less than the 71 sustained during the 1979 demonstration period. A major objective of CHAP has been to develop information that will be transferable to other metropolises.(7) In 1980 the Survey will be distributing two reports, one dealing with the accuracy of their continuous storm rainfall measurements and with the accuracy of their 30, 60 and 120 minute predictions. The other report will be essentially a users' manual relating to the topic of how to choose the radar-raingage mix for any given metropolitan application.

RADAR CALIBRATION

McGill meteorologists have observed that most of their radar measurements are within the 2 mm/hr to 25 mm/hr range. MIT meteorologists contend that: "Unless observations are made with exceptionally fine resolution, a value of 100 mm hr^{-1} seems a reasonable upper limit for rainfall rates measured with a radar. It is recognized that considerably higher rates often occur within thunderstorms, but they cover such small areas that it would be unrealistic to assign a higher value for an average over the 'point' covered by the radar (an area on the order of 10^5 m^2 or more)."(1)

Noted earlier was that McGill routinely generates digital CAPPI grid maps for a curved 3 km elevation plane above the ground. "In convective storms the reflectivity is fairly constant with height up to 4 km or more, so that there is unlikely to be any significant discrepancy between the precipitation viewed by the radar and that which reaches the surface except at extreme ranges."(1)

MIT meteorologists have expressed reservations ~~on~~ the use of raingages to calibrate radars during the progress of a storm. "In the case of thunderstorms, unrepresentative sampling by the gauges could lead to inappropriate and possibly dangerously misleading adjustments to the radar measurements. If, for example, a small, intense cell passed very close to the gauge but not directly over it, or if there were hail in the storm, greatly enhancing the reflectivity, it might appear that the radar was grossly overestimating the rain. An overly large downward adjustment made to all indicated rates might cause some severe storms to be judged much less intense than they actually are. For widespread rain, where radar errors are likely to be range dependent, corrections indicated by comparison with the gauge would not be suitable over the entire area. Although automatic calibration by gauges appears dangerous, use of gauges for regular monitoring is strongly recommended. The observer could note any discrepancies, determine their cause and decide whether a correction is warranted and how it should be implemented."(1)

Records of upwards of 100 raingages have been used to calibrate the McGill radar. Because the bulk of these raingages are of the non-recording type, 24-hour accumulations from radar and raingages have been compared. The calibrations have been made subsequent to the termination of storms.

The Illinois State Water Survey position appears to be in harmony with the above views. A high level of calibration precision should be attainable in the Chicago area because of the uniquely extensive recording raingage network employed from 1976 to 1978. During the 1979 demonstration period, a dual "calibration-adjustment" procedure was employed. To the extent possible, when a storm was expected, the radar calibration, based on prior raingage network measurements, was checked to insure that the radar was working properly. During the demonstration period, this calibration was adjusted as needed every 30 minutes to reconcile rainfall depths telemetered from the 22 MSD raingages. Much of the real-time adjustments were made manually, by default, because of certain computer delays, although automatic real-time adjustments from raingage rainfall measurements had been planned. In a dedicated full-time system, adjustments should probably be resolved automatically. On the other hand, Survey meteorologists advise against too much reliance on automation and stress the importance of supervision by a meteorologist in the rainfall measurement and prediction process. In the same vein, they emphasize that local governments using the rainfall data generated should be involved in the processing of that data, even though communication might be limited to telephone discussions between the radar staff and the local agency's operating center. Fairly obvious is that prospective users of such data should be heavily involved with the radar facility staff from the outset.

A mathematical model for prediction of short-term rainfall for urban hydrology applications(16) might be useful as a means for checking or refining digital radar calibrations. Testing of the model was performed for: a synthetic storm on a synthetic 36 raingage network; two storms on the 142 raingage network of the Agricultural Research Service, Southern Great Plains Watershed Research Center, in Chickasha, Oklahoma; and two storms on the 200 raingage network of the Illinois State Water Survey, METROMEX project, in metropolitan St. Louis.

NATIONAL PROGRAMS

The NOAA Weather Service has five digital radar record installations, at the University of Miami, Pittsburgh, Kansas City, Oklahoma City and Monett, Missouri. While the Weather Service has vigorously sought to upgrade its oldest radars and progressively add a digital recording capability to its 117 radars, because of budgetary and specification constraints it will be the early 1980's to the mid-1980's before modernization will be completed at the other NWS radar sites.

In contrast, the Canadian Atmospheric Environment Service has eight digital radar record installations, all situated in metropolitan areas. Canada thus appears to be moving faster than the U.S. on this, but they seem to favor 5 cm radars whereas 10 cm radars are more suited to urban hydrology applications.

In 1978 a 5 to 8 year pilot project was initiated in the United Kingdom with the objective of improving precipitation forecasts up to several hours ahead for the benefit of local government water management agencies.(17) Four digital recording radar installations are involved, two of which have 10 cm radars and all of which are intended to be operated 24 hours a day. "The radars will be calibrated in real-time using a number of clusters of telemetering raingauges, each cluster comprising at least two raingauges."(17) Radar indications will be augmented through use of satellite imagery. Radar rainfall data on a 5 km grid will be transmitted every 15 minutes via telephone to remote users. The broad intended users group has been described.(18) Progress is reported regularly by the Radar Research Laboratory.(19)

Feasibility of linking a weather radar to a computer in which an optimum reservoir operating program is stored, as well as a program of a hydrologic rainfall-runoff model producing the reservoir inflow hydrographs from radar-measured rainfall data, has been explored in the Federal Republic of Germany for two small adjoining river basins 34- and 56-km^2 (13- and 22-mi.^{2}) in size.(20) Further, for the two basins, synthetic hydrographs computed from radar-measured rainfall were found to be of the same accuracy as those obtained from a special dense raingage network (one recording gage per 25-km^2 or one per 10-mi.^{2}) set up for research purposes in the same area.(20)

IMMEDIATE PROSPECTS FOR OPERATIONS APPLICATIONS

Local governments in the Montreal and Chicago metropolitan areas are favored with an operational and a near-operational facility, respectively. What about other urban centers? In many cases, the cost of installing, operating and maintaining a dedicated radar system would seemingly be prohibitive for a single service provided by a single local government. Pooling of resources for multiple service use by several local agencies in a metropolitan area has potential. Possibly a more realistic direction would be in cooperative ventures with the National Weather Service (NWS) and, in Canada, the Atmospheric Environment Service.

The ranges of the 117 radars operated by the NWS span many U.S. metropolitan areas. In many cases, local government operational control interests could be accommodated by adding computer capability at the NWS radar, augmenting the staff of meteorologists at the NWS radar, and installing suitable tie lines. Several urban areas have telemetered raingage networks that could be reporting to a NWS radar facility as easily as they now do to local agency dispatchers. However, NWS radars serve a host of national and regional needs, and their multi-purpose use might be a constraint. Also, it is our understanding that NWS radars are not calibrated as often as local needs would seem to dictate, that they are not always operated in the continuous scanning mode required for local government use, and are not necessarily operated around the clock. The calibration and operational services provided by the NWS should improve in the future with the implementation of the Radar Processors (RADAP's) presently being procured by the NWS. The RADAP's are scheduled for implementation at approximately 75 of the NWS radar installations over the next five years. RADAP's provide on-site digital data processing and communication capabilities.

A major objective of a report on the feasibility of storm tracking for automatic control of combined sewer systems(21) was to facilitate communication between civil engineers and meteorologists on associated local government needs. That report served as an introduction for discussions with meteorologists that led to the findings in this Section. It appears safe to say that an active and effective dialogue is definitely under way.

PLANNING AND DESIGN IMPLICATIONS

Control of urban runoff pollution and flooding must be based on probabilities of occurrence because of the randomness of precipitation. More precisely, the interpretive foundation must be in terms of the mean recurrence or mean return period or mean frequency of occurrences. Five-minute data that commonly spans fifty years or more from local National Weather Service first-order stations is the primary long-term rainfall data base for the planning and design of urban drainage in any metropolis. Only one such station exists in nearly all metropolitan areas, becoming the sole source of long-term data almost everywhere. Thus far, attempts to simulate 5-minute single-point data via stochastic methods have been completely unsuccessful, leaving single-point historical records as the unique source.

As a result, it is necessary to assume that the long-term single-point record would be more or less replicated over a similar period of time at any other point in the same metropolis. This is a generous assumption because we have proof of spatial persistence only for individual pieces of storms, namely maximum intensities separately for each specified duration, as presented in maps of maximum average rainfalls for specified durations and average frequencies of recurrence reported by Yarnell in 1935,(22) as further generalized by the Corps of Engineers in 1945,(23) and as greatly refined in 1961 in U.S. Weather Bureau Technical Report No. 40(24) and recent updates. These national maps connect equal values of rainfall for a given duration and frequency, but these values are for different storms at different years from one location to another along any "isohyetal". Thus, there is an implication of long-term persistency in magnitudes from one point to another over long distances, and hence over relatively short distances, tenuously based on the documented strong persistence of amounts of separate pieces of storms regarded independently in time and space.

Acquisition of a long-term 5-minute rainfall record for a National Weather Service first-order station can be costly and very time consuming. The lack of ready access has been a contributing factor in the popularization of the use of synthetic storms for planning and design. Indiscriminate use of synthetic storms, commonly called "design storms," can lead to costly and misleading results, particularly when pollution abatement and/or detention storage are involved.(25) The pros and cons of design storms were enumerated at a 1979 international seminar at Montreal.(26)

The artifices described above are resorted to by the more astute specialist by default. What the urban drainage planner and designer in a given place really need is a long-term record of 5-minute rainfall data expressed in terms of reliable average depths for each drainage catchment of interest. To have this kind of data would have required the making of measurements in a dense network of raingages distributed over the metropolis and spanning a period of twenty years or more. There are only a handful of U.S. metropolitan areas where even a crude approximation of these requirements is met.

In 1977 the National Weather Service reported on a study started in 1974 to derive geographically-fixed point-area relationships from digitized radar data: "Digital radar data can be expected to provide both spatial resolution and geographical coverage far in excess of those from dense network gage data."(27) On the other hand: "Storm rainfall amounts based on combined radar-gage data have average errors of about 10% to 30%. This figure is for gage densities similar to that of the National Weather Service Climatological Network (1 gage per 1000-km^2 to 2000-km^2). While the error may decrease further as the gage density increases, the advantage of radar diminishes since sufficiently dense gages alone provide about the same accuracy as the combined data. It is estimated that for midwestern United States thunderstorms this becomes the case for gage densities greater than about 1 per 250-km^2 to 400-km^2."(28)

Using data from a network of 15 gages with a density on the order of 1 per 40-km^2 in metropolitan Chicago, a model has been developed by the NWS that is based on the covariance structure of storms and deals with depths, areas, durations and return periods.(29) While the goal of the study is "to determine areal average precipitation that has the same frequency of occurrence as point precipitation ..... over the United States east of the Rocky Mountains, where most of the radars are located,"(27) it will take some time to verify the suitability and reliability of the evolving findings for urban drainage applications. Also, "it will be some years before sufficient digitized radar data have accumulated to form reliable annual maximum series"(29) if, indeed, records for only a few years prove to be too short for this purpose.

In 1977 the Stormy Weather Group of McGill University extended its radar measurement and prediction project to include an exploration of areal rainfall distributions.(30) Indicated mean hourly rainfalls for 323 clock hours of rainfall from a number of storms were calculated for area sizes in multiples of 1 to 96 times a unit size area of 36-km^2, and were expressed in terms of their probability. The number of area samples varied between 257,000 for the unit size area to 75,000 for an area 96 times as large. At low probability levels the largest size area had a mean rainfall on the order of about half that for the 36-km^2 unit size area. At high probability levels the differences tended to disappear. It is planned to analyze more recent radar measurements to ascertain joint frequencies of a fixed point rainfall (long-term record station) and mean rainfalls on urban drainage catchments in the Montreal region that range downward from about 40-km^2 in size, or down from about the smallest size area of 36-km^2 used in the 1977 study. Also, an attempt will be made to use as small as a 5-minute time interval in the analysis, together with 10-minutes, 15-minutes, 30-minutes and one hour.

During the summers of the five-year period 1971 through 1975, the Illinois State Water Survey pursued METROMEX (METROpolitan Meteorological EXperiment) in the St. Louis metropolitan area.(31-33) Included in the extensive instrumentation deployed was a dense network of 225 recording raingages within 2,000-mi. (5,200-km^2), a gage spacing of approximately 3-mi. (4½-km), or about one gage per 9-mi.^{2} (20-km^2). All rainfall records were reduced to 5-minute interval amounts. Total storm depths have been studied for various groupings of raingages, four raingages on about 36-mi.^{2} being the smallest. During 1980 consideration will be given to a correlation analysis of hourly and possibly shorter time interval rainfall amounts at the NWS gage at Lambert International Airport just outside St. Louis and average amounts for fixed sectors in the metropolitan area. The smallest sector might be 18-mi.^{2} in downtown St. Louis, with larger sectors being a radial enlargement beyond this core to embrace an area as large as 200-mi.^{2} on the western side of the Mississippi River. Should more raingage data accumulate in the Chicago area,(7-13) it may be possible to consider a similar analysis for that data and to make inferences for numerous municipalities over the very large surrounding region by exploiting radar archives of the Survey's CHAP and its successor research.

OTHER POTENTIAL USES

While this section has focused on short-range (up to 2 or 3 hours) quantitative anticipation of rainfall using radar, it is important to reiterate that regional synoptic expectations at longer time frames (2 or 3 to 24 hours) can be extremely important in automated operation of urban runoff systems. Insofar as precipitation influences air pollution growth and decay,(34) there are possibilities of integrating weather watches for air pollution conjointly with runoff considerations.

"Digital radar have application to at least three important hydrologic problems: flash flood warning, river stage forecasting, and urban hydrology. Within the present framework of the NWS Office of Hydrology mission, only flash flood monitoring and river stage forecasting are presently being addressed."(35) Potential uses of digital recording weather radar for metropolitan flood warning systems are explored in the next

Section. The most urgent need in urban hydrology from a planning and design standpoint is realistic and reliable catchment mean rainfalls related to a reference raingage historical record in each and every metropolis, as explained in the preceding subsection.

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SECTION 6

METROPOLITAN FLOOD WARNING SYSTEMS

by M. B. McPherson[a] and William G. DeGroot[b]

INTRODUCTION

It is generally agreed that complete automatic control of combined sewer systems will require the use of the special new radar capabilities described in Section 5. In a given metropolitan area, such a special radar installation backed by calibrating raingages could also serve as part of a metropolitan flood warning system. A central thesis of the present report is that the attractiveness of automatic control of urban runoff may be expected to increase as the territory served becomes larger and the number of functions served increases. Thus, the purpose of this presentation is to review prospects from a metropolitan flood warning system perspective, focusing on leading-edge initiatives in the Denver area.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

The National Weather Service (NWS) of the National Oceanic and Atmospheric Administration (NOAA) has been developing for several years a capability for real-time processing and analysis of radar data by automatic computer to improve its river basin hydrological forecasting techniques.(1) In opposition to the river basin scale, flash floods are associated with thunderstorm rainfall, which occurs over fairly small areas. According to the Director of the NWS, "the flash flood has recently become the most dangerous weather phenomenon of them all".(2)

The American Meteorological Society has urged NOAA to take several steps, including: expand the implementation and improve upon Local Flash Flood Warning Systems (LFFWS); and improve the ability to monitor and detect flash flood conditions, by increased use of automated ground measurements, radar, weather satellites, and improved communication systems.(3) The new Federal Emergency Management Agency (FEMA) will take on some of the flood warning activities but NOAA will focus on hydrometeorological aspects. Among the four NOAA FY 1979-84 Program Objectives is: "Develop the basis for nationwide implementation, at the local level, of regionally coordinated flash flood programs. ..... Over 650 LFFWS's are in place."(4)

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There is every indication that NOAA is moving towards more extensive service to metropolitan areas. Symptomatic is the NOAA Prototype Regional Observing and Forecasting Service (PROFS) program under development at its Environmental Research Laboratories in Boulder, Colorado. This Section includes a description of parts of the PROFS program relevant to this report. PROFS commenced in October, 1979.

METROPOLITAN DENVER

The Urban Drainage and Flood Control District, a metropolitan special district headquartered in Denver, Colorado, has responsibilities in an area covering about 1,200 square miles of all or parts of six counties. Several streams passing through its jurisdiction have upstream tributaries covering an additional area in excess of 1000 square miles, and some of these originate at the Continental Divide. A flooding early warning system for the Denver area has been contemplated for some time.(5) In May, 1978, the District initiated the "Westerly Creek Flood Warning Plan,"(6) which incorporates the warning of possible flash floods from the NWS on the basis of storms detected at its Limon, Colorado, radar station, a network of rainfall observers, and staff gages at major ponds. The Westerly Creek Flood Warning Plan is continually updated and revised.(7) More recently, the District has initiated the "Boulder Creek Flood Warning Plan,"(8) which is the focus of attention in most of the remainder of this Section. The Boulder Creek plan that has been adopted is one of the alternative plans considered in a 1977 engineering report.(9) Contemplated are similar plans for other basins, the gradual automation of portions of these plans and, ultimately, an overall metropolitan plan with maximum effective use of automated features.

Upon completion of the Boulder Creek study in 1977, the District formulated a two-pronged flash-flood warning plan consisting of an areawide system capable of providing basic meteorological information to all 34 local governments within its jurisdictional area, and specific warning systems for individual drainage basins. The concept was to provide improved weather radar coverage and meteorological support for the entire District area first, and then to develop complete warning systems for individual basins.

The District plays several roles in the development of a basin warning system. During the planning phase it meets half of the planning costs, with the other half met by the local governments affected. Also, the District manages the planning effort. In order for District funds to be used for the implementation of a basin plan, the local governments affected must agree to assume ownership of and provide maintenance for facilities and equipment, regulate or manage the basin flood plain, and to have a comprehensive warning plan in effect.

BOULDER CREEK(9)

Boulder Creek drains through the center of Boulder, Colorado. Where the creek enters the city it has a drainage area of 132 square miles, originating along the Continental Divide and traversing a straight-line distance eastward of about 20 miles, Figure 8. Main stem and tributary branches are quite steep, with the highest elevation along the Divide being

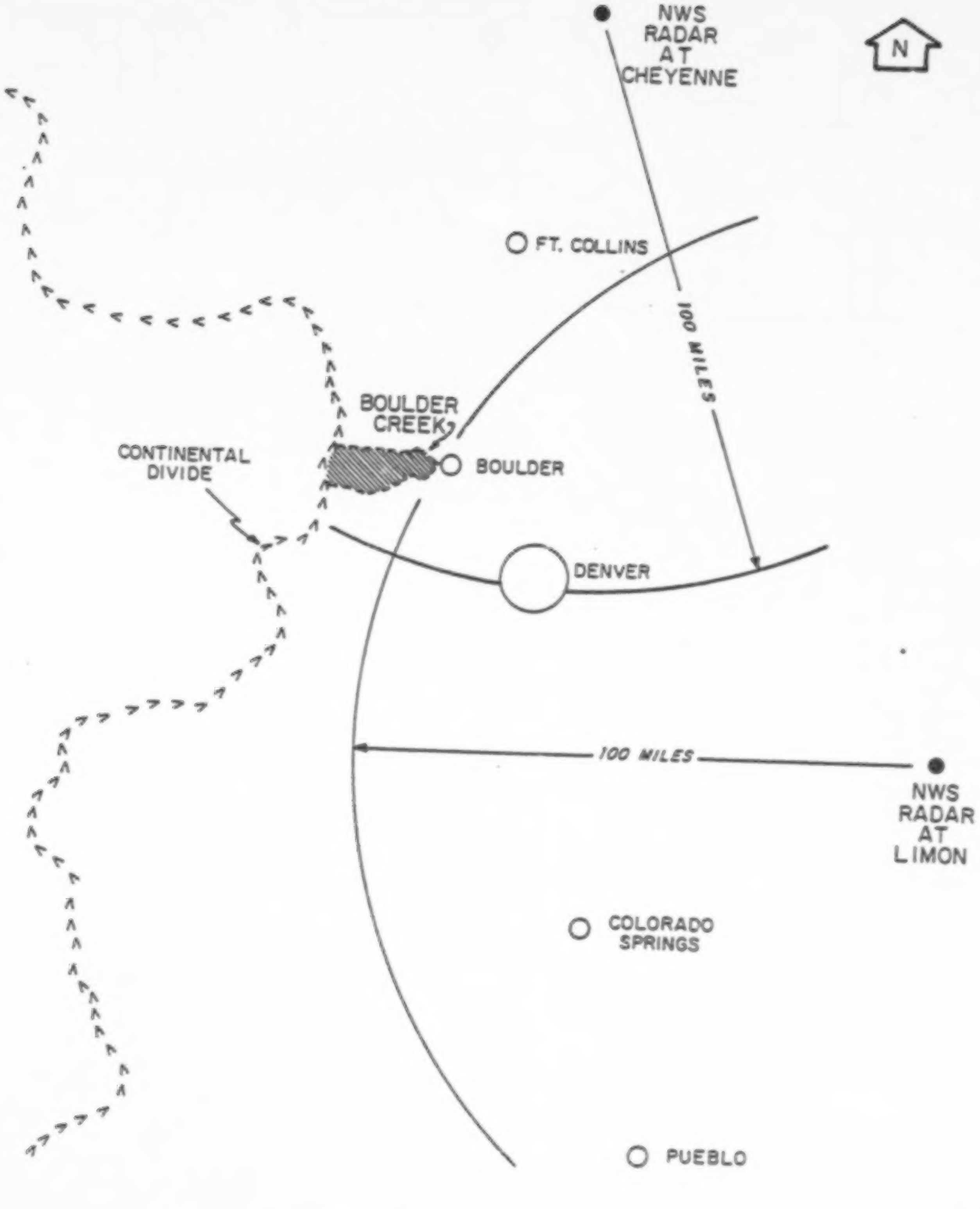
NWS
RADAR
AT
CHEYENNE
N
FT. COLLINS
100 MILES
BOULDER
CREEK
CONTINENTAL
DIVIDE
BOULDER
DENVER
100 MILES
NWS
RADAR
AT
LIMON
COLORADO
SPRINGS
PUEBLO

FIGURE 8 - BOULDER CREEK AND RADAR SITES

13,400 feet compared with about 5,400 feet at Boulder; and 15% of the basin lies above an elevation of 11,000 feet and 46% is above 9,000 feet. In the higher portion, there are numerous small lakes fed by snow melt, and a number of glaciers exist at the Divide. There are several small towns and settlements within the basin above Boulder. The basin is particularly susceptible to flash floods originating in the steep mountain canyons of the foothills, due to the steep slopes and elongated tributaries, mostly from high-intensity, short-duration thunderstorms that occur from May through September.

A Flood Warning Plan Evolves

Almost since its establishment in 1859, the City of Boulder has experienced flooding from the streams that pass through it. "Flooding of Boulder Creek in 1965 and 1969 caused extensive damage and revived interest in flood plain management and emergency planning."(9) These and other considerations accelerated adoption of a flood warning plan for Boulder Creek. A galvanizing influence was the July, 1976, catastrophic flooding of the Big Thompson River, only about 30 miles north of Boulder, where well over one-hundred people lost their lives.(10)

In response to a request from the City of Boulder, the Omaha District of the Corps of Engineers has made a study of flood mitigation measures that might be applied in the urban reaches of Boulder Creek. Three alternative plans were proposed by the Corps of Engineers, featuring an enlarged channel or an excavated floodway or relocation and floodproofing. Flood warning was an element of all three alternative plans. In the course of the study, the Corps of Engineers made numerous hydrologic analyses for various points within the basin and estimated the discharge and flood plain inundation of a 100-year flood passing through Boulder. Although Boulder has not settled on a total flood mitigation plan, it proceeded with the flood warning element in cooperation with Boulder County and the Urban Drainage and Flood Control District.

The District, Boulder and Boulder County retained a consulting engineering firm to evaluate flood detection alternatives.(9) Human behavior considerations transcend technical matters in flash flood warning systems, and the Urban Drainage and Flood Control District commissioned concurrent studies of those issues.(10,11)

Armed with drafts of the engineering report,(9) the report on behavioral response to the Big Thompson River calamity(10) and the study report on expected behavioral response in Boulder,(11) a two-day workshop was held in Boulder in May, 1977, attended by representatives of federal, State and local agencies and private citizens to discuss implementation of a suitable warning system for Boulder Creek. A major question that arose in the workshop was the feasibility of using radar in combination with the types of systems surveyed in the engineering report,(9) that might provide a more cost-effective flood detection system and that could be expanded beyond to other basins served by the Urban Drainage and Flood Control District. In response to this question, possibilities for incorporating radar surveillance were included in the final draft of the engineering report.(9)

The Boulder Creek System(8)

Following submittal of the three 1977 final reports,(9-11) the District, Boulder and Boulder County developed a plan for the Boulder Creek flood warning system. The system consists of a flood detection and evaluation element and a written plan element.

The flood detection element will soon include: eight automated raingages and four automated stream gages which telemeter data to a central location; a series of manual raingages and stream gages, the operation of which is assigned to volunteer fire departments in the Boulder Creek drainage basin; and meteorological observations, including the use of weather radar, by the National Weather Service and GRD Weather Center (Geophysical Research and Development Corporation, Lakewood, Colorado). The latter is a private firm that has been retained by the District to assist the NWS in connection with flood warning services for communities within the District's service area. By the end of 1979, seven of the automated raingages had been installed, the volunteer fire departments had been assigned raingage and stream gage responsibilities and meteorological observations had been well started. The other automated gages will be installed in 1981. Consideration is being given to the costs and benefits of still greater commitments to hardware and the introduction of software, and obvious economies of scale require that such evaluations be made in a total metropolitan area context. This metropolitan-wide perspective is entirely consistent with Urban Drainage and Flood Control District services, inasmuch as it is assisting communities within the District in the formulation and implementation of flood warning plans.(12)

The written plan element of the warning system includes the assignments of responsibilities for action by all participating agencies, from the onset of storm conditions conducive to flooding through flood warning and evacuation of the flood plain. Preparation of the plan for Boulder Creek was by the District, the City of Boulder, Boulder County and the University of Colorado, assisted by the National Weather Service, the GRD Weather Center, Leonard Rice Consulting Water Engineers and the Corps of Engineers.

As a means for meeting any type of disaster, including flash floods on Boulder Creek, a Multi-Agency Resource System (MARS) has been formulated by the City of Boulder, Boulder County and the University of Colorado at Boulder. MARS has three components: a Board of Directors (locally elected officials); a Situation Information Center (SIC); and a Resources Allocation Center (RAC). The SIC, the first component of MARS to be activated, is responsible for collecting, evaluating and displaying all hydrologic and hydraulic data and for advising the Board of Directors on flooding situations as they develop. The RAC will assign and account for resources under supervision of the Board of Directors. The Boulder Creek Flood Warning Plan was written so as to mesh with MARS.

Boulder is the County seat, and the Situation Information Center (SIC), conveniently located in the office of the County Sheriff, is the nerve center of the flood warning system, Figure 9. The main purpose of the warning system is to reduce possible loss of life, and includes the three basic

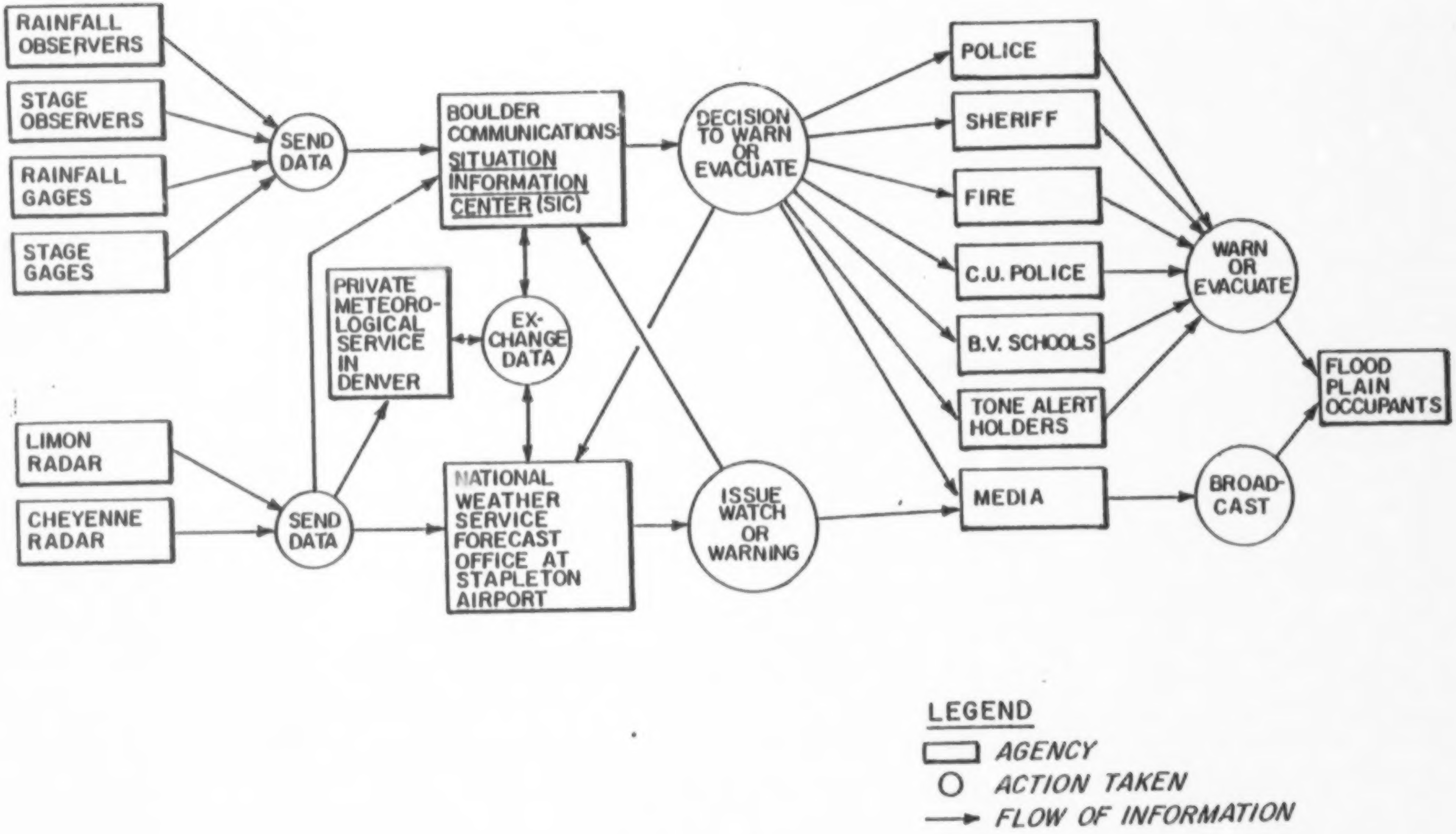
RAINFALL OBSERVERS
STAGE OBSERVERS
RAINFALL GAGES
STAGE GAGES
SEND DATA
LIMON RADAR
CHEYENNE RADAR
SEND DATA
PRIVATE METEOROLOGICAL SERVICE IN DENVER
BOULDER COMMUNICATIONS: SITUATION INFORMATION CENTER (SIC)
EX-CHANGE DATA
NATIONAL WEATHER SERVICE FORECAST OFFICE AT STAPLETON AIRPORT
DECISION TO WARN OR EVACUATE
ISSUE WATCH OR WARNING
POLICE
SHERIFF
FIRE
C.U. POLICE
B.V. SCHOOLS
TONE ALERT HOLDERS
MEDIA
WARN OR EVACUATE
BROAD-CAST
FLOOD PLAIN OCCUPANTS
LEGEND
AGENCY
ACTION TAKEN
FLOW OF INFORMATION

FIGURE 9-FLOW CHART OF BOULDER CREEK FLOOD WARNING PLAN(8)

components of a complete system: detection and evaluation of floods; dissemination of warnings; and response to warnings. Although all three components must function properly if the warning system is to succeed, discussion hereinafter will dwell exclusively on technical aspects of detection and evaluation. Feasibility of any warning system hinges as much about effective dissemination of and response to warnings as it does with regard to effective detection and evaluation. (An analysis has been made of dissemination modes available nationally.(13)) Before embarking on the technical aspects, mention must be made of the two types of advisory information that are disseminated to the public: a "watch," which means that a flash flood could develop; and a "warning," which means that a flood is already occurring or is imminent. These alerts can be issued by the NWS and be relayed by Boulder Communications. A "watch" status was reached twice in 1979 but a "warning" situation did not arise.

Returning to Figure 9, the "rainfall observers" and "stage observers" refer to rainfall collected at each of the 10 fire stations west of the foothills and to about 11 stream gages monitored by personnel from fire stations. The network of automated raingages and stream gages telemeters signals to the SIC at Boulder Communications. Rainfall and runoff data are currently employed solely in a reactive mode, with basic information on unfolding events being used together with other information in a rule-curve approach to arrive at subjective judgments about immediate prospects of flooding. Initially, tables provided by the NWS are the principal guides to be used. As data from the network accumulates, it is planned to develop at least a hydrologic analysis capability and perhaps also a hydrologic predictive capability. Overall operations of the Situation Information Center (SIC) are depicted in Figure 10.

Use of Radar

Two NWS radar installations are located in the Denver region, Figure 8, at Limon, Colorado, to the east and at Cheyenne, Wyoming, to the north. Because the maximum useful range of a network weather radar, from a hydrological viewpoint, is about 200 km (125 miles), Boulder Creek is within the marginal ranges of both radars. Such weather radars have a cathode-ray tube which displays small dots of light on the face of its fluorescent screen that are an analog transform of radio waves returned to the radar antenna by intercepted rainfall. The brightness of a dot on the display depends on the strength of the returned signals, or the "echo intensity," and generally the greater the mass of precipitation at a "point" in space, the greater the corresponding display point brightness (echo intensity) on the scope. Echo intensities are normally discriminated into six levels of dot brightness. Ranges of rainfall intensity have been ascribed to each of the six brightness levels, termed "Video Integrator Processor" (VIP) levels, as follows:(14)

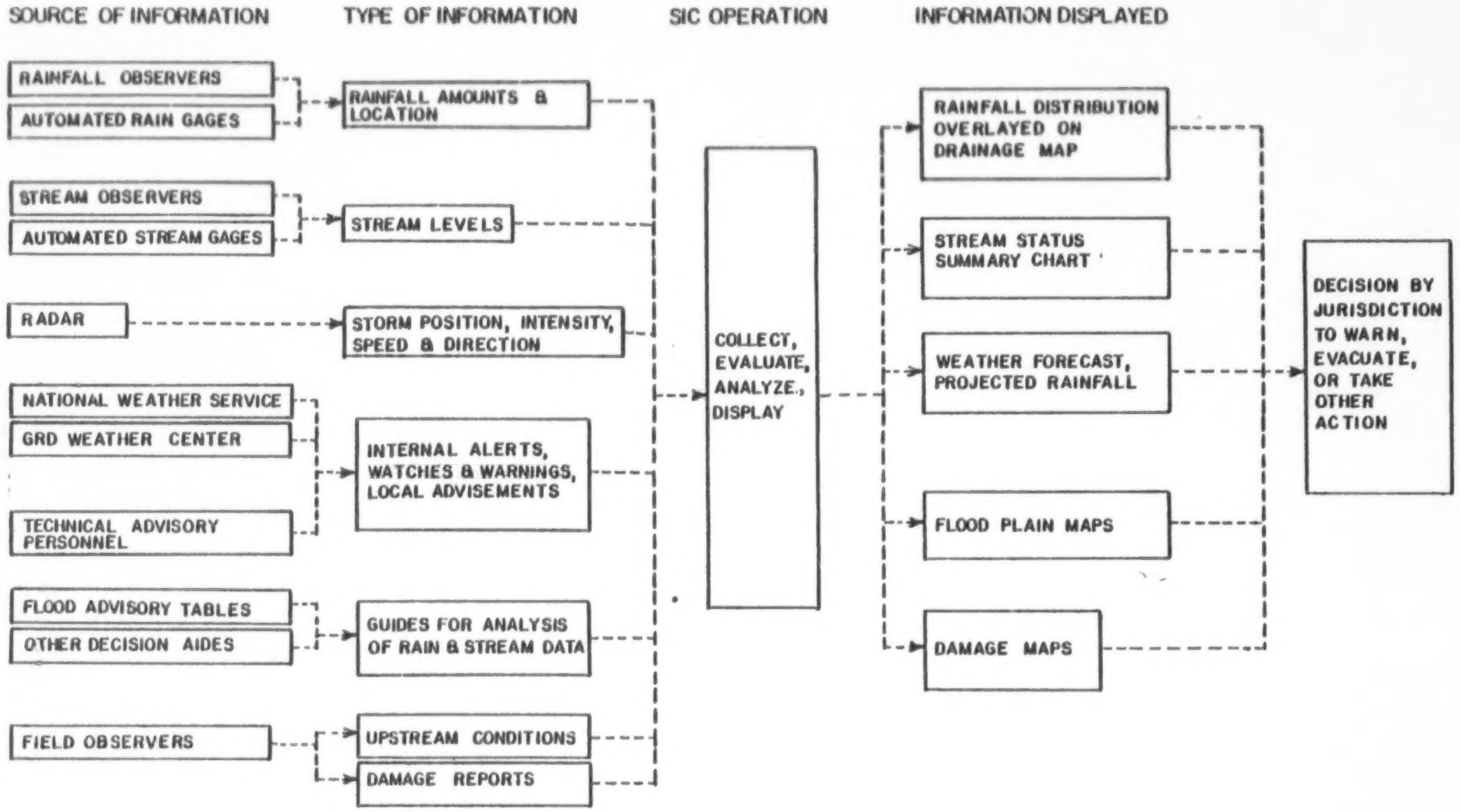
SOURCE OF INFORMATION
TYPE OF INFORMATION
SIC OPERATION
INFORMATION DISPLAYED
RAINFALL OBSERVERS
AUTOMATED RAIN GAGES
RAINFALL AMOUNTS & LOCATION
STREAM OBSERVERS
AUTOMATED STREAM GAGES
STREAM LEVELS
RADAR
STORM POSITION, INTENSITY, SPEED & DIRECTION
NATIONAL WEATHER SERVICE
GRD WEATHER CENTER
TECHNICAL ADVISORY PERSONNEL
INTERNAL ALERTS, WATCHES & WARNINGS, LOCAL ADVISEMENTS
FLOOD ADVISORY TABLES
OTHER DECISION AIDES
GUIDES FOR ANALYSIS OF RAIN & STREAM DATA
FIELD OBSERVERS
UPSTREAM CONDITIONS
DAMAGE REPORTS
COLLECT, EVALUATE, ANALYZE., DISPLAY
RAINFALL DISTRIBUTION OVERLAYED ON DRAINAGE MAP
STREAM STATUS SUMMARY CHART
WEATHER FORECAST, PROJECTED RAINFALL
FLOOD PLAIN MAPS
DAMAGE MAPS
DECISION BY JURISDICTION TO WARN, EVACUATE, OR TAKE OTHER ACTION

FIGURE 10-SITUATION INFORMATION CENTER (SIC) OPERATIONS[8]

VIP Level	Echo Intensity	Rainfall Rate (Convective Conditions) in./hr.	mm/hr.
1	Light	< 0.2	< 5
2	Moderate	0.2 to 1.1	5 to 28
3	Strong	1.1 to 2.2	28 to 56
4	Very Strong	2.2 to 4.5	56 to 114
5	Intense	4.5 to 7.1	114 to 180
6	Extreme	> 7.1	> 180

In 1979, the Urban Drainage and Flood Control District purchased equipment that displays VIP levels in six different colors, rather than black and white, and in a grid pattern, rather than as an assemblage of dots. These devices, together with their supporting modules, are called "Color Computer Remote Radar" or "C2R2" by their manufacturer. Radar installation interfaces were installed at Limon and Cheyenne and video receivers were put (Figure 9) in the NWS Forecast Office at Stapleton Airport (located at the northeastern edge of Denver), at the office of the private meteorological service in Lakewood, just west of Denver (GRD Weather Center), and at the SIC in Boulder. Under a cooperative agreement with the NWS, the equipment on NWS property is on loan from the District. Signals from the Limon and Cheyenne radars are connected by microwave link to an interrupter station of Mountain Bell in Denver and relayed from there by telephone line to the NWS Forecast Office at Stapleton Airport and to the GRD Weather Center in Lakewood. (The Limon radar is a WSR-57 and the Cheyenne radar is a WSR-74c). Communication with NWS-Stapleton and SIC-Boulder by the GRD Weather Center is also via telephone. Coupling of NWS forecasting service with a private meteorological service, under the aegis of the District, was the first instance of such a cooperative arrangement. The costs of GRD Weather Center services are borne solely by the District.

At the close of 1979, the color displays were instantaneous, although they could be enlarged and shifted to focus on discrete sectors and an image could be "frozen" for closer scrutiny. Display storage capability has since been added.

On the basis of their study of earlier scope photographs from the Limon radar, meteorologists of the GRD Weather Center have a strong suspicion that the genesis of local convective storm cells is just beyond the foothills near the mountains to the west. Another such birthplace appears to be formed by Palmer Ridge, located between Denver and Colorado Springs. Further, such storms appear to follow mostly a few rather definite tracks. If orographic influences indeed force convectional rainfall into more persistent than usual paths and directions, there are possibilities for exploiting these tendencies. Priorities among basins for flood mitigation, flood warning service and abatement of pollution from runoff might be adjusted to account for any persistent wide spatial disparities documented for the microclimate. The new radar signal display facilities, guided by "ground truth" from raingages, are being used to further explore the storm path persistence hypothesis, the future use of such facilities for more basins, and the possible role of such facilities in future hydrological forecasting and water quality assessment. Capability for this evaluation was greatly enhanced when radar signal display storage was added in 1980.

A possibility for increasing the analytical scope would be the addition of digital radar recording capability of the type developed by McGill University and the Illinois State Water Survey (see Section 5). However, while fully appreciating a great potential for measurement, District engineers have reservations about Boulder Creek with regard to rainfall and runoff forecasting because it backs up all the way to the Continental Divide, has very varied topography and presents a number of unusual hydrologic complexities. That is, it is possible that the present capability, when nominally augmented, for tracking, anticipating and measuring rainfall, may prove to be adequate and to be the limit of feasible complexity for Boulder Creek. However, there are a number of other basins in the Denver region further from the mountains where rainfall prediction using digital recording radar might prove more fruitful.

On the other hand, Boulder Creek is rather unique in a jurisdictional sense. The area tributary to the City of Boulder and the City itself are in a single County, with no cities or large towns upstream, and the City happens to be the County seat. Most of the other basins in the Denver region contain more than one city or large town and several are in more than one County. Local governments are extremely reluctant to yield their authority for issuing flood warnings and evacuation notices to another local government or to a partnership of local governments. Linking advanced technology to seriousness of need can become complicated or clouded by administrative, jurisdictional and legal issues.

Features of the Boulder Creek Flood Warning Plan have been described in two American Meteorological Society papers.(15,16)

PROTOTYPE REGIONAL OBSERVING AND FORECASTING SERVICE (PROFS)

In October, 1979, the NOAA initiated the first phase of PROFS, the concept of which "has the ultimate goal of providing the nation with radically improved local scale weather services. In order to accomplish this goal, recent progress in observing and forecasting methods, data processing techniques, and modes of dissemination will be integrated to produce improved forecast accuracy and responsiveness to local weather conditions. This new capability is designed to fill the local service gap that is a primary reason for substantial weather-caused loss of life and economic inefficiencies, and will become an integral part of our existing synoptic scale services."(17) The first phase is presently scheduled over a four-year period and will be conducted at the NOAA's Environmental Research Laboratories in Boulder, Colorado, by a newly formed Exploratory Development Facility (EDF) using the weather data network in the Denver region, which will be greatly expanded for that purpose.

"The PROFS plan calls for the creation of the research prototype of a greatly improved local weather service capability. It will integrate technological advances into a single flexible system designed to provide radically improved local weather services that are fully responsive to user needs."(18) To reiterate, the local-scale system to be developed under PROFS will be designed to complement NOAA's existing synoptic-scale services.(19)

Of particular interest here is the forecast capability envisioned for PROFS.(19) This would include a guidance forecast, over a period of 12 to 24 hours in advance, such as the recognition of the possibility of impending severe thunderstorms, based on continental weather intelligence. From such a severe thunderstorm guidance forecast, the local forecaster would be alerted to the possibility of employing the local predictive capability for the 0-hour to 12-hour time-frame. A high-resolution numerical model, if called upon, would then be used to produce 3-hour to 12-hour predictions, narrowing the suspected region of severe storm activity. As the forecast lead time reduced to within 3 to 6 hours of the expected event, the model would be used to produce more refined predictions of the time and location of severe storm activity. "At less than 3 hours before the event, the numerical model would cease being a central part of the forecast procedure. During this shorter time-frame, the forecaster would rely on near-real-time observations and sophisticated extrapolation techniques that are preprogrammed and available for immediate call-up from a mini-computer. As the storms develop, the watch area could be further narrowed to a highly specific warning area."(19)

"The National Weather Service has statutory responsibility for providing the public with disaster warnings. ..... The urgency of the flash flood problem is such that it deserves special mention. ..... PROFS encompasses the entire range of local weather service needs, while the NWS flash flood initiative deals with the single requirement to provide more effective weather service in flood prone regions. A second difference is the amount of time that will elapse between the beginning of the programs and operational implementation. The flash flood plan is designed to use off-the-shelf technology to produce an early improvement in our present flood warning capability. PROFS, on the other hand, seeks to make optimum use of new research capabilities and will take considerably longer to design and implement the proposed new total local weather service. The NWS program will provide an important early test bed for PROFS subsystems that are suited to the flash flood problem. As PROFS matures, the flash flood program will receive the benefit of complete local weather systems that incorporate high technology devices and equipment. Because PROFS will employ this technology to address many problems in addition to flash floods, flood prone regions will eventually have access to equipment and techniques that would not be cost-effective if used for the single purpose of flood warnings."(17)

The Denver region happens to be particularly prone to flash flooding. By a very fortunate coincidence this is the region serving as the mesoscale developmental field laboratory for PROFS and embraces the metropolitan area and its environs where flood warning capabilities are being developed in the nationally forefront program under the aegis of the Urban Drainage and Flood Control District described above. In 1980 PROFS and the

District initiated a cooperative project expected to continue through 1982. Effectiveness in the use of measured and predicted rainfall from a digital recording radar in conjunction with hydrologic models for flood warning will be explored. Plans call for testing with three basins that have suitable field instrumentation and to which a hydrologic simulation model has already been applied. Rainfall predictions by PROFS will be for at least up to two hours in advance.

We understand that at the end of the four-year first phase of PROFS an exploratory local weather service will be in operation in the Denver region. At that time, the EDF of PROFS expects to transfer operational responsibility to the NWS for it to upgrade the exploratory system to prototype specifications. During this second phase of PROFS, the EDF will upgrade certain components, as necessary.

METROPOLITAN MELBOURNE

In 1976, the ASCE Urban Water Resources Research Program was privileged to issue as one of its Technical Memoranda a compendium on urban flood warning and watershed management advances in metropolitan Melbourne, Australia.(20) Part II of that report describes the computer-operated, telemetered gage network for flood forecasting and prediction of the Melbourne and Metropolitan Board of Works. The field gage network was deployed mostly on the lower extremities of three streams that pass through metropolitan Melbourne. The total drainage area of the Yarra River where it discharges into Port Phillip Bay at Melbourne is about 5,400 km^2 (2,000 sq. mi.). The drainage area of the Maribyrnong River, where it enters the Yarra River near its mouth at the Bay, is 1,400 km^2 (540 sq. mi.); Merri Creek, with a drainage area of 400 km^2 (150 sq. mi.) enters the Yarra River further upstream; and thus these two streams together comprise about one-third of the total Yarra River drainage area. In 1976 the field gage network included 15 remote stations located within a radius of 60 km (37 mi.) from the operational center, which is about 10 km (6 mi.) from the mouth of the Yarra River. Three of the 15 stations recorded both rainfall and runoff, two recorded rainfall only, and the other 10 recorded stream levels. Nine stations were located within the Maribyrnong River catchment, three were within the Merri Creek Catchment, and three were along lower reaches of the Yarra River.

These three streams are among several that pass through or are contained within the about 1,300 km^2 (500 sq. mi.) jurisdictional area of the Melbourne and Metropolitan Board of Works and that drain extensive rural tracts, with serious potential dangers of flooding due to runoff from such large drainage areas. In 1976, signals from the 15 field stations were transmitted every six minutes via dedicated lines to a control center where a mini-computer processed and stored the received data on magnetic-tape cassettes for subsequent analysis. The primary function sought at that time was real-time monitoring, so that telemetered information from the remote stations could be used to trigger flood alerts when pre-set conditions were attained. Different types of alarms were displayed at the control center, which was manned around the clock. Flood forecasting was mostly accomplished off-line from the monitoring system. Successful operation of the system justified the installation of additional computer capacity. An expansion of the network from 15 to 45 stations was envisioned, including stations in other catchments. Planned was the development of a real-time modeling capability together with decision algorithms for flood forecasting. A possible role for radar data was envisaged. Initial development was to center on adaptation of a hydrological model from nearby Monash University.(21) "No reference on relevant published material has been found on how to integrate these techniques, so this work is being done within the Board."(20)

Updating information was supplied by Mr. C. T. Earl, Chief Engineer of Main Drainage, Melbourne and Metropolitan Board of Works, in correspondence dated 16 March 1979 and 7 January 1980. By mid-1978, the rainfall-runoff monitoring network had been fleshed out to include all planned 45 stations, distributed among a number of catchments. There were 26 raingages and 41 level gages involved for the 45 stations. The technical staff was preoccupied mostly with adapting enlarged computer capabilities to process the constantly growing volume of data generated over the 1976-1978 period. However, a hydrologic computer model called the Catchment Response Model was developed by the staff and tested against data for the Maribyrnong River and Yarra River. Progress had been made on the development of a real-time modeling capability, but advances had been hindered by certain limitations of the facilities available. Despite the availability of a network of 32 raingages by 1979, it has not been possible to obtain a detailed understanding of the size of storm cells or the activity within cells or to obtain an accurate picture of the movement of cells. The staff yearns for the availability of a suitable radar installation to augment its raingage network. Mr. Earl expects that times available to issue flood warnings for major streams in Melbourne would be several hours longer than in Boulder and notes that the main danger from flooding in Melbourne does not seem to arise so much from thunderstorms over dry catchments but from frontal type rains which may cover wide areas and wetter catchments that are mostly rural. Thunderstorm problems possibly are limited to the smaller urban areas, which react to such storms so quickly that it is virtually impossible to give any warning. The Board hopes to enlarge its telemetry system to 150 data collection stations from the current 66 stations.

Some related Australian activities deserve mention. A short-term flood forecasting model has been successfully tested on a 25 km^2 catchment near Sydney;(22) however, hydrologic aspects but not decision variables have been addressed and the tests were post facto rather than in real time. Also, the tests were considered satisfactory for moderate and large floods only with rainfalls of "reasonably uniform spatial distribution".(22) Hearsay has it that implementation of a metropolitan flood warning system has been initiated in Brisbane. This system had its origins in a study reported in 1976.(23)

COMPARISON OF APPROACHES

Encouraging is the use of digital recording radar for flood forecasting in Alberta, Canada,(24) where the foothills and eastern slopes of the Rocky Mountains are particularly flood-prone. However, the Alberta River Forecast Centre deals with a basic forecast unit of 250-1,000 km^2 (100-400 mi^2). As in Melbourne, flash floods are of less concern than in the

Denver area, because floods from the eastern slopes "generally result from heavy widespread rain falling for several days".(24) As a result, the lag time between precipitation events and high water conditions is much greater than for Denver area basins, permitting comparatively much more time for hydrologic analysis and evaluations.

Melbourne chose a near-total system monitoring approach whereas Denver plans to use more of a basin by basin accretion. An important factor that must be considered in any such comparison is that the Melbourne system was initiated in 1974 with a commitment for one-third of the ultimate network of stations whereas the Denver system evolved in response to local government interest, first in the Westerly Creek Flood Warning Plan of 1977 and second in the Boulder Creek Flood Warning Plan of 1979. The later start-up of the Denver system has had the advantage of accessibility of the latest technology, and advances in hardware in recent years have occurred almost too rapidly to keep track of them. Perhaps the biggest difference is that Denver focused on dissemination of and response to flood warnings guided by hydrologic indications, and left any elaborate detection and evaluation of floods as a capability to be developed gradually against a background of total metropolitan potential needs. Melbourne appears to have focused on detection and evaluation of floods, with dissemination of and response to flood warnings resolved as experience with the monitoring system accumulated. Further, the Melbourne and Metropolitan Board of Works is fundamentally an operating agency, with a large technical staff, whereas the Urban Drainage and Flood Control District has only four engineers and currently has limited operating responsibilities, the execution of which are contracted out, and relies heavily on the fiscal and administrative cooperation of various units of general local government on such endeavors as flood warning plans.

SATELLITE SUPPORT

Data from polar orbiting and geostationary weather satellites are used by hydrologists of the National Environmental Satellite Service (NESS) of the National Oceanic and Atmospheric Administration to make, among several things, precipitation estimates for convective weather systems. Resolution is as small as 1-km. Because polar orbits occur twice per day, although data therefrom can be used to identify areas of substantial flooding on large rivers it cannot be used reliably to detect flash floods.(25) However, half-hourly data from two geostationary satellites have been used to estimate rainfall in a 1977 storm that caused serious flash flooding in metropolitan Kansas City.(25) Post facto comparisons of satellite indications with hourly raingage measurements were deemed quite comparable although measured amounts were higher for part of the storm. Overall satellite indications were consistent with those obtained from the local weather radar.

The Space Science and Engineering Center of the University of Wisconsin/Madison has developed the Man-computer Interactive Data Access System (McIDAS) to facilitate making precise cloud motion measurements from meteorological satellite images. A current research project at the Center has the objectives of developing methods for improving short-range weather forecasting techniques through the use of McIDAS for the processing and application of satellite, surface, radiosonde and radar data.(26) While the System is used almost exclusively for research at the Center, an exploratory tie connects it to NESS in Kansas City. Using satellite data from McIDAS tapes, a comparison with hourly rainfall measurements from raingages and radar for a 240-km^2 area in Texas indicated that such data can provide reliable estimates of convective rainfall amounts.(27)

Thus, a potential exists for real-time blending of local weather radar prediction not only with the twice-daily synoptic forecasts of the National Weather Service but also on forecasts from half-hourly satellite readings. However, when an operational capability might become available to local governments for the latter is presently uncertain.

CONCLUSION

We can conclude that real-time flood forecasting in individual metropolitan areas has eluded full implementation and demonstration. However, from this and the preceding Section it is evident that a technological breakthrough is imminent. With a variety of agencies nibbling at the edges of this issue, in North America and elsewhere, it should be safe to expect a breakthrough by 1984 and it is conceivable that this might happen as early as 1982. Access to reduced and interpreted satellite data by local governments would seem to be very desirable in metropolises where prediction lead times in excess of two or three hours might otherwise not be adequate.

Considerations in the response of the mass media to alerts and warnings of flash floods have been included in the proceedings of a national workshop on disasters.(28) Practices in several nations in the hydrological forecasting of floods are detailed in a report of the World Meteorological Organization.(29)

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